Investigation of Light-off Temperature and Conversion Efficiency of Electrically-Heated Catalyst

Undergraduate Honors Thesis

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ABSTRACT

As concern for the environmental issues become more severe, emission regulations are becoming more stringent. To meet increasing demands of emissions regulations, industrial leading auto maker try to replace the conventional gasoline vehicles by renewable vehicles such as EVs (electrical vehicles) and PHEVs (Plug-In Hybrid Electrical Vehicles). Although these renewable vehicles decrease the annual emission greatly, the manufacturing cost and operational range are primary constrains to prevent the mass production in large scale. On top of this, TWC (Three-Way Catalyst) is the current solution to reduce the emission on the conventional vehicles. But it is limited during the cold start because it can be functional only if the temperature is above light-off temperature.

To eliminate the limitation of operational temperature, EHCs (Electrically Heated Catalysts) have been proposed as a solution. This technology can be particularly helpful for PHEVs to reduce the emissions following a cold start event. One challenge for implementation on PHEVs is that they typically have low current capability in the 12-volt system that supplies the EHCs. EHCs often require more than 100 amps from a 12-volt system for 50-60 seconds making it difficult to use in a PHEV. This research is focused on investigating the relationship between emission conversion efficiencies and light-off temperature to achieve the desired emission reduction goal. A wide range of light-off temperature with constant power supply and air mass flow rate are tested to study thermal and chemical characteristics of the EHC. Emissions data during these tests are collected and studied to determine the best possible solution for lowering emissions while staying within the constraints of the 12-volt system. These results are used to develop a control strategy for OSU's EcoCAR vehicle which will compete in a national competition in May of 2017.

ACKNOWLEDGEMENT

First, I would like to sincerely thank for my advisor Dr. Shawn Midlam-Mohler. His constant and genuine advice and supports in the past one year for my research. He is willing to take his valuable time from the busy schedule to teach the overall knowledge of the vehicle control, to brainstorm the control development process, to discuss testing results and to review every single writing material for me. With the experience of this research, I got my hands dirty working on every single component on the vehicle. My passion in the vehicle control was practiced and kept for my future graduate study.

I would also thank for Dr. Marcelo Canova for being a member of my defense committee. My presentation could not be better without his showing to my oral defense.

My research could not be accomplished without the countless helps from the EcoCAR 3 team member. They included Andrew Johnson, Aditya Modak, Brandon Bishop and Wilson Perez. I want to show my special thanks to Wilson Perez where we spent so many days brainstorming, testing, analyzing and developing control strategy for the EHC heating from stretch to functional codes.

I also want to appreciate my parents for sending me to college in the US. My family worked diligently in the past four years to assure that I could have equal opportunity of receiving college education in the major that I am passionate about.

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1. Introduction

1.1 Background

As the society develops after the second industrial revolution, air pollution is becoming more severe in the modern age. Most air pollutions are the side products of manufacturing industries, but more obvious air pollutions are emitted by the vehicles. In the 21st century, vehicles have served as the primary method of transportation for most people in daily life. As the number of vehicles increases dramatically in recent decades, the environmental issues such as greenhouse effects and global warming caused by the air pollutions from the vehicle emission become the urgent problems that human beings need to deal with.

To cope with these environmental issues caused by the vehicle emission, much research has been done in this field to understand the constituents, the potential harmful effects and solutions to eliminate the vehicle emissions. It has been discovered that the primary contents of the vehicle emissions are CO, THC and NOx. [1] Among them, the harmful gases such as CO, THC and NOx are the main contents that influence the environment and human health in a large scale. It has been discovered that CO (Carbon Monoxide) is a poisonous gas formed by the incomplete burning of fuels. The HC (Hydro Carbons) is an air pollution that contained the hydrogen and carbon emitted from the unburned and partially burned fuel from the engine exhaust. The HC is formed if the fuel evaporates directly into atmosphere. The NOx (Nitrogen Oxides) is a generic term to represent the air pollution that contains various percent of nitrogen and oxygen due to burning fuels at high temperature. [1] The environmental effects of emission include not only the environmental issues in both small and large scale but also the human health issues. Air pollution will cause different environmental effects in the modern society. For instance, these air pollutants cause the human health issues such as lung cancers, respiratory system disorder and allergies. In addition to that, they also cause the environmental issues such as photochemical smog, acid rain and the destruction to the ozone. In a large scale, it causes the greenhouse effect and global warning. [1] The full results table that includes the list of air pollutants and the harmful effects of the air pollutants was shown below in Table 1.

Table 1 Formation and Environmental Effects of Emissions Gases [1]

Pollutant	Anthropogenic Source	Environmental Effect
Nitrogen oxides (NO + NO2)	High temperature fuel combustion—motor vehicles, industrial, and utility	Primary pollutants that produce photochemical smog, acid rain, and nitrate particulates. Destruction of stratospheric ozone. Human health impact.
Carbon monoxide	Rich & stoichiometric combustion, mainly from motor vehicles	Human health impact
Carbon dioxide	Fossil fuel and wood combustion	Most common greenhouse gas
Particulates	Combustion of biofuels such as wood, and fossil fuels such as coal or diesel	Reduced atmospheric visibility. Human health impact. Black carbon particulates contribute to global warming.
Sulfur dioxide	Coal combustion, ore smelters, petroleum refineries, diesel engines burning high-sulfur fuels	Acid rain. Human health impact.

1.2 Current Solution

To create a sustainable environment for the development of industrial world and a comfortable atmosphere for the human health of generation, researchers delicately focus on eliminating vehicle emissions from different aspects. For example, as we all know, a lot of researching funding has been distributed to explore how can we replace the conventional gasoline vehicles by renewable vehicles such as EVs (Electrical Vehicles) and PHEVs (Plug-In Hybrid Electrical Vehicles). As we can see from the Table 2, the annual cost of emission of these renewable vehicles are one-third less than those of conventional gasoline vehicles. The annual cost of emission of these renewable vehicles are well-to-wheel emissions calculated by considering the emissions costs of material, fabrication and transportation. Although the emissions of renewable vehicles on the road are much less the emissions of conventional vehicles, there are still many inevitable constrains for these renewable vehicles such as the operational temperature, cost of manufacturing and battery energy density.

As most automakers state, the high-performance batteries store most energy to power the motion of the vehicles for both acceleration and patrolling. “A warm battery cranks the car engine better than a cold one. Cold temperature increases the internal resistance and lowers the capacity. A battery that provides 100 percent capacity at 27°C (80°F) will typically deliver only 50 percent at –18°C (0°F). The momentary capacity-decrease differs with battery chemistry”. [2] In fact, there is a large chance of living in low-temperature areas during the winter time such as Northern Europe, North America and North Asia. The countries in these areas such as Canada, Northway, Finland, Russia and the US are all populated densely areas. Hence, renewable vehicles are not as good as the conventional vehicles run by the traditional fuels such as diesel and gasoline in these extremely cold conditions.

On the top of this, the manufacturing cost is another factor that needs to be taken into consideration. Due to the high requirement of the battery packages, additional costs will be made to design, produce and assemble larger battery package onto these vehicles. As a result, more steps will be added to the fabrication process. From a financial perspective, the prices of these renewable vehicles are much higher than conventional vehicles although the savings from better fuel consumption could compensate part of extra payment of the vehicles itself for the consumers. From the report of The National Academies Press, the incremental costs of PHEVs would not decrease significantly in near future of 20 years. In Table 2, it showed a numerical estimated future PHEV incremental costs.

Table 2 Incremental costs of PHEVs in the Future [3,4]

	2011	2015	2020	2030
PHEV-40	14,100-18,100	11,200-14,200	9,600-12,200	8,800-11,000
PHEV-10	5,500-6,300	4,600-5,200	4,100-4,500	3,700-4,100

Currently, two major battery technologies used in EVs are NiMH (Nickel Metal Hybrid) and Li-ion (Lithium Ion). Nearly all HEVs available in the market today use NiMH batteries because of its mature technology. Due to the potential of obtaining higher specific energy and energy density, the adoption of Li-ion batteries is expected to grow fast in EVs, particularly in PHEVs and BEVs. [3,4] However, the battery energy density is also a big concern when leading auto makers try to replace the conventional vehicles by renewable vehicles because the driving range greatly limited the use of the them. The increasing number of electric power infrastructures is a temporary solution to this problem. But the increasing number of electric power infrastructures could also be issues for two reasons. Although the use of renewable vehicles could decrease the emissions such as NOx, THC and CO, the generation of electric power would produce more CO2 because most of electric plants rely on fossil fuels for the production. [3,4] Moreover, "Power demand varies during the day, peaking during the afternoon and reaching a low point after midnight. It also varies over the year, with demand highest on summer afternoons because of air conditioning loads. Parts of the U.S. electric power system are at full capacity during these hours of highest demand, and additional loads could threaten reliability unless new capacity is added." [3,4]

In the future, the renewable vehicles will find their way to become an indispensable part of our daily life. But more researches need to be done in this area to improve the performance of the battery in the extreme temperature conditions and to lower the manufacturing cost. In conclusion, due to the limitation of the renewable vehicles mentioned above, they could not be generalized in a large scale. Hence, the vehicle emissions need to be decreased by considering other solutions on conventional vehicles.

In the current market, the most frequent solution to reduce the emissions is to use TWC (Three-Way Catalyst). TWC reduces the emission by taking place a series of chemical reactions in the exhaust after-treatment system. From the previous paragraph, we already know that the primary emission gas needed to be reduced are CO, NOx and THC. This TWC could catalyze the chemical reaction if the temperature of the TWC reached the required temperature. This temperature termed as light-off temperature.

The following balanced chemical equation will illustrate the chemical process inside the TWC. [5]

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

$$2CO + O_2 \rightarrow 2CO_2$$

$$2C_3H_6 + 9O_2 \rightarrow 6CO_2 + 6H_2O$$

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

$$2H_2 + O_2 \rightarrow 2H_2O$$

$$2CO + 2NO \rightarrow N_2 + 2CO_2$$

$$C_mH_n + mH_2O \rightarrow mCO + m + nH_2\,2$$

However, the only limitation on this current solution to the conventional vehicle is that the chemical reaction can only happen if the light-off temperature is in the range from 270 $°C$ to 350 $°C$. In fact, the temperature of the TWC cannot reach light-off temperature when the vehicles experience the cold-start event where the engine is started for the first time after 10 hours. The major vehicle emissions are emitted during the cold-start event. In other words, the solution of TWC is good at eliminating the vehicles emission only if the EHC is warmed up by the heat transfer from the high-temperature emissions gas. The temperature of emissions gas is raised by the flammable explosion inside piston cylinders. To further reduce more vehicle emissions, particularly in the cold-start phase, a pre-heating TWC is proposed to be used. In this research, EHC (Electrically-Heated Catalyst) will be installed onto the PHEV in the EcoCAR 3 competition team to develop a control strategy for pre-heating EHC.

1.3 EcoCAR 3 Competition Team

The EcoCAR 3 project is a four-year competition sponsored by General Motors and the U.S. Department of Energy challenging 16 university team to reengineer a 2016 Chevrolet Camaro to a Plug-In Hybrid Electric Vehicle. In this competition, the team in The Ohio State University designed a parallel hybrid electric vehicle to achieve the equal fuel performance while reduce the exhaust emissions. Overall, the technical requirements of this competition are to reduce the energy consumption, reduce wheel-to-well greenhouse gas emission and keep consumer acceptability in the areas of performance, safety and utility with the consideration of cost and innovation.

1.3.1 EcoCAR Emission an Energy Consumption.

The Emission and Energy Consumption Event will be evaluated in the following four equally-weighted areas [5]:

- On-road fuel consumption
- Well-to-wheel petroleum energy usage
- Well-to-wheel greenhouse gas emissions
- Regulated tailpipe emissions (NO_X, THC, CO)

In the competition of year 3, EcoCAR 3 team is given an opportunity to perform the chassis dynamometer emissions testing at the TRC in the East Liberty, this testing includes time-resolved measurements with a portable emissions measurement system.

1.3.2 Ohio State EcoCAR Plug-In Hybrid Electric Vehicle

The Ohio State EcoCAR 3 vehicle is a post-transmission parallel PHEV. The unique vehicle architecture of each hybrid vehicles allows for a unique set of vehicles operating modes. In this project, the main vehicle operating modes for the OSU EcoCAR vehicles are as an electric vehicle and a charge sustaining hybrid allowing for a total vehicle range above 200 miles. Figure 1, is a representation of the EcoCAR 3 vehicle’s architecture. A 2.0 L naturally aspirated E85 compatible engine, 150 kW (peak) Electric Motor (EM), 32 kW Belted Alternator Starter (BAS), 5-speed Automated Manual Transmission (AMT) and an 18.9 kWh lithium ion battery pack are used on the vehicle as the main powertrain components. This vehicle is capable of driving in all-electric mode for a range of 44 miles with improved charge sustaining fuel economy. The dynamic performance allows the vehicle to accelerate from 0 to 60 mph in just 5.6 seconds. [6]

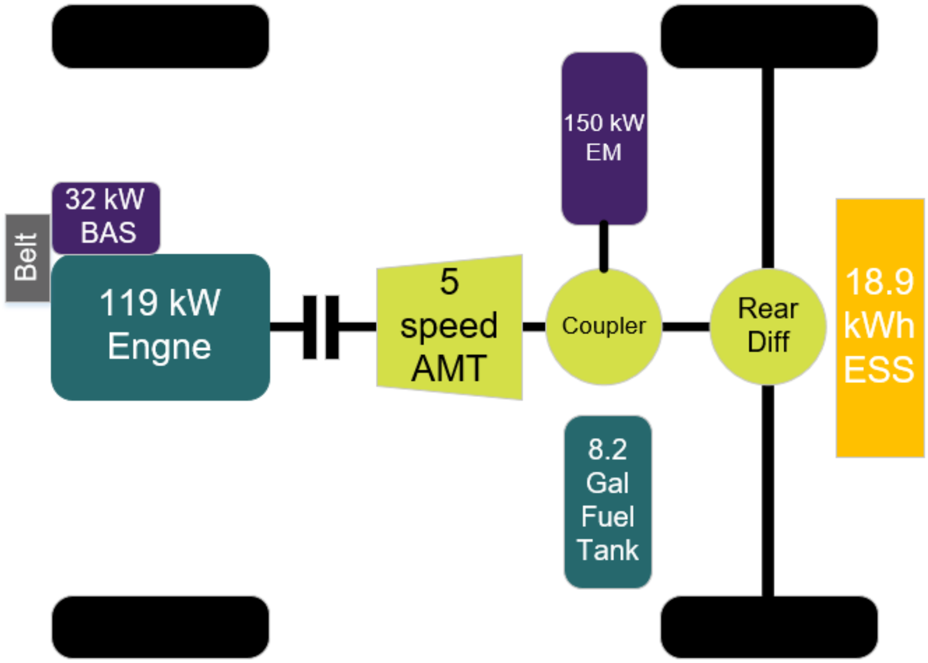

Figure 1 Hybrid Architecture of EcoCAR 3 Vehicle [6]

In this research, this unique architecture of The Ohio State University's EcoCAR vehicle offers a great opportunity to draw a highly-demanding power from the DC-DC converter. DC-DC converter basically convert the power in the high-voltage battery to 13.4 volts that matches the vehicle operating voltage. In this research, EHC will take advantage of this high-voltage battery to draw more than 100A current for 50 - 60 seconds. A solid-state relay will be used to supply the power from DC-DC converter to the EHC. An ECU command will be used to control the voltage from the DC-DC converter to avoid the battery voltage drop caused by overdrawing current. [6]

The major distinction between the PHEVs with the EHC heating and conventional vehicles with the EHC heating is that the PHEVs can operate in electric mode. The electric mode allows the user to drive the vehicle while the vehicles wait for the EHC warm-up.

1.4 Electrically-Heated Catalytically Converter

EHC is a catalytically converter that will be preheated by high-current power to reach the light-off temperature. Usually, the preheating is required if the engine is turned off for more than 6 hours which is considered as the cold-start. To have a better performance of the EHC on the vehicles, much research has been done to investigate electrically pre-heating the catalytic converter. Two major research fields on the EHC are energy consumption and mechanical durability. First, the physical characteristics of the EHC such as mass, geometrical surface area, cell density and electrical resistance of the EHC construction can be optimized to save energy. [6] Researcher also conducted thermo-cycling, vibration analysis and high mileage durability tests to understand thermomechanical durability behavior. The research in this field can help improve the mechanical durability of the EHC. [7]

1.4.1 EHC Hardware Design

The EHC is an actively-controlled device that will be integrated into the upstream of the main catalyst of the vehicle exhaust system to lower the cold-start emissions specifically. The EHC is made with alternating smooth and corrugated layers of thin, metal foil connected to each other by a brazing process. Typically, the resistance of this foil structure is from 0.05 to 0.35 ohm. It will be connected to the positive and negative electrical terminals of a solid-state relay. The solid-state relay is served as a switch to turn on and off the power supply from the parallel circuit between vehicle battery and DC-DC converter. The EHC heating structure is heated up through electrical resistive heating. The air flow from the engine exhaust then transfer the heat from the heating elements to the main structure body of the EHC by flowing through the entire cylinder. Therefore, the main catalyst can reach its light-off temperature more quickly rather than wait for being heated by the exhaust gases from engine. In Figure 2, it shows that the heating elements are inserted into the EHC in the upper structure.

Figure 2 Photo of Electrically-Heated Catalyst

In this research, the EHC will be installed on the upper stream of the main catalytic converter right after the exhaust collector for two reasons. The air flow can directly go through the heating elements. This closed-coupe location allows less loses air flow from the engine Hence, shorter time and less energy are required to crank the engine during EHC heating phase. On the top of this, this closed-couple location takes advantage of the heat transferred from the exhaust gases when the engine operates in its normal condition.

1.4.2 Air Injection

A constant supply of air flow is required to transfer the heat from the heating elements at the beginning of the EHC to heat up the catalytically converter to the light-off temperature. From the previous research, most researchers have applied a secondary air injection pump before the EHC to supply the constant the air flow rate. This additional device takes extra packaging space, adds up external weight to the vehicle and consumes more electric energy. To improve the vehicle in the aspect of weight, cost and energy consumption, a method is proposed to generate sufficient air flow by using BAS (Belted Alternator Starter) to crank the engine in electric mode before the engine starts. In chapter 4, more details about the air flow rate testing will be found. This research will explore the characteristics of the air flow rate by cranking the engine with the fully-open and fully-closed throttle positions.

1.4.3 Electrical supply

A high current will be drawn from the DC-DC converter to supply the power to EHC before the engine starts. The high-demanding current drawing from the DC-DC converter would potentially causes a vehicle blackout if the battery voltage drops below 12 volts. This vehicle blackout can be a hazard to throw the error signals and disturb the functionality of the supervisory controller. To avoid dropping voltage below 12 volts, a ECU signal will be created to control the current drawing from the DC-DC converter. If the supervisory controller detect that the battery voltage drops below 12 volts, it will send a command to draw more power from DC-DC converter to keep the battery voltage above 12 volts. More details will be explained in chapter 4.

1.4.4 Control Strategy

Many researches have been done in the past to investigate the benefits of pre-heating and post-heating control strategy for the EHC. In this research, a pre-heating control strategy will be utilized to heat up EHC during the cold-start event when the fuel is enriched. Typically, supervisory controller injects more fuels than it needs when the engine starts for the first time during cold-start because the air/fuel ratio is determined by the calibration files of this engine from the manufacturers. The air/fuel ratio will become accurate only if the supervisory controller is in the closed-loop. The closed-loop control allows engine to receive the feedback signals from the sensors that are installed at various vehicle components. In this research, a closed-loop control is preferred before the engine starts. The control strategy will take charge of EHC pre-heating phase before the engine starts. It will first check the BAS enable first; check the air mass flow rate; draw the corresponding power from parallel circuit; check the temperature of the EHC and fire the engine at an approximate engine speed eventually.

1.4.5 EHC Vehicle Application

In the past years, the EHC is rarely used on the vehicles that are on the mass production line for several reasons. First, the highly-demanding requirement of current drawing can barely be achieved by 12-volt battery that is used to start the engine and maintain the electronical system of the vehicles. Besides, the manufacturing cost of the EHC is too expensive to install on the vehicle as a component in the mass production. But the historical data show that the EHC has been implemented on the production vehicles before. This technology has only been used on the low volume vehicle platform. As the Eurpean and U.S. emissions regulations become more stringent, Emitec EHC units are integtrated into the BMW ALPINA B12 from 1991 to 1996. This BMW ALPINA B12 is a luxurious business class sedan that is redesigned based on the BMW 7 series limousine. As the paragraph mentioned before, the trade-off between emissions reductions and electrical demands, manufacturing cost and added weight is taken into consideration when facing the marketing challenges. Eventually, the emissions improvements are achieved by the advanced emission control techniques. Hence, EHC technology is not developed into the mass production phase yet in vehicles today.

1.5 Objectives

The installation of EHC is the key to the successful vehicle emissions reduction, particularly useful for the PHEVs. However, the low current capacity on the 12-V battery system make it challenge to implement the EHC. The first objective of this research is to determine the best possible solution for lowering emissions while staying within the constraints of the 12-volt system. To achieve this goal, a control strategy will be developed for the EHC pre-heating phase. Along the development of control strategy, the relationship between the emission conversion efficiency and light-off temperature will be investigated to discover the power it just needs to achieve the mission of emissions reduction with lowest power consumption in the shortest time

In the past research, the air flow that transfers the heat from heaters to warm up is typically generated by the secondary air injection device. This device is installed in the middle way between exhaust manifold and the EHC. To save the energy consumption, reduce the weight and save the space for packaging, this research is going to conduct the air flow rate testing by using the BAS (Belted-Alternated Starter) to crank the engine in electric mode. In this research, some control criteria including the air flow rate, power supply, heating time and engine firing RPM will be explored to help develop the control strategy.

This thesis will discuss the control strategy development process on The Ohio State University EcoCAR 3 team's PHEV. It consists of a detailed document of the research background and motivation; logic of control strategy; a wide range of experimental testing results and in-depth analysis of the experimental results. An overview of the chapters contained in this thesis is provided below.

Chapter 2 – Design and Fabrication of EHC

This chapter will introduce the design and fabrication process of the EHC components, summarize the list of testing sensors and explain the installation methodology.

Chapter 3 – Control Strategy Development

This chapter mainly focused on how does the control flowchart is developed and refined as the testing results are published. Then, the implementation of control logic will be illustrated in the Stateflow in Matlab Simulink.

Chapter 4 – Experimental Testing and Results

This chapter will discuss what testing this research has been done to refined the control criteria.

Chapter 5 – Validation

This chapter will verify the proper functionality of the EHC heating control strategy on the Vehicle. Besides, the emissions testing with and without EHC heating will be conducted on the chassis dynamometer to verify the performance of the EHC.

Chapter 6 – Conclusion and Future Work

This chapter will summary the experimental testing and reach a conclusion of the control strategy. Some possible improvements for the current research and future focus on the research will be discussed at end of this section.

2 Exhaust System Design and Testing Bench Setup

2.1 Exhaust Design and Fabrication

The entire exhaust system design and fabrication are accomplished in house at CAR in The Ohio State University. The design of the exhaust system must meet requirements of packaging space, light weight, and low cost. In Figure 3, the exhaust collector is designed based on the actual space on the left side of engine header. This exhaust collector directly collects the exhaust gases from pipes of four cylinders. The tightly square shaped collector saves weight and space to achieve the light weight requirement.

Figure 3 Photo of the Exhaust Collector

As the design moves from exhaust collectors to EHC transitional pipes, the exhaust cones and flanges are designed to weld the exhaust collector with EHC main body together. In Figure 4, the three-bolt flanges and exhaust cones are designed using Solidworks. Two identical three-bolt flanges and exhaust cones were manufactured in house using stainless steel at pre-CAT and post-CAT positions as the connecting components with other main structures of the EHC.

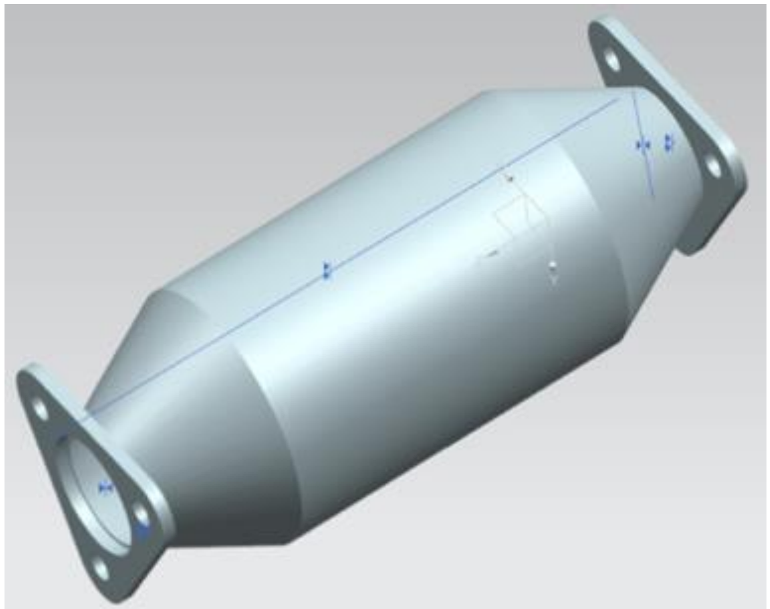

Figure 4 EHC Cones and Flanges Design

In Figure 5, it showed the entire finished exhaust system. This exhaust system was made in the EcoCAR 3 team. This exhaust system was installed onto the dyno engine to do the thermal and chemical characteristic testing of the EHC. Some testing sensors such as oxygen sensors and RTDs (Resistance Temperature Detectors), and emission compression fittings were incorporated into this set of exhaust system for the testing purposes. Eventually, the exhaust system included only two oxygen sensors and one RTD at mid-CAT location for the control purposes. As the picture showed, two compression fittings for two oxygen sensors were welded at most outside location. Two RTDs were welded at mid-CAT and post-CAT locations. They were all welded along the axial direction for an easier packaging purpose. The compression fittings were welded in the opposite position to the oxygen sensors to avoid the installation interference.

Figure 5 EHC with Compression fittings of O2 sensors, RTDs and Exhaust Emissions

2.2 Data Acquisition Setup

The primary data that would be collected in the thermal testing were temperature data in the mid-CAT and post-CAT location; and the emissions data at pre-CAT and post-CAT location. Both data in this data acquisition setup were real time data began from the engine cold-start. In Figure 6, it showed a user interface of the LabVIEW setup for the temperature data acquisition. The instantaneous temperature could be read to monitor the temperature change. During the thermal testing, the power supply to the EHC would be cut off once the temperature of the mid-CAT location reached the desired light-off temperature.

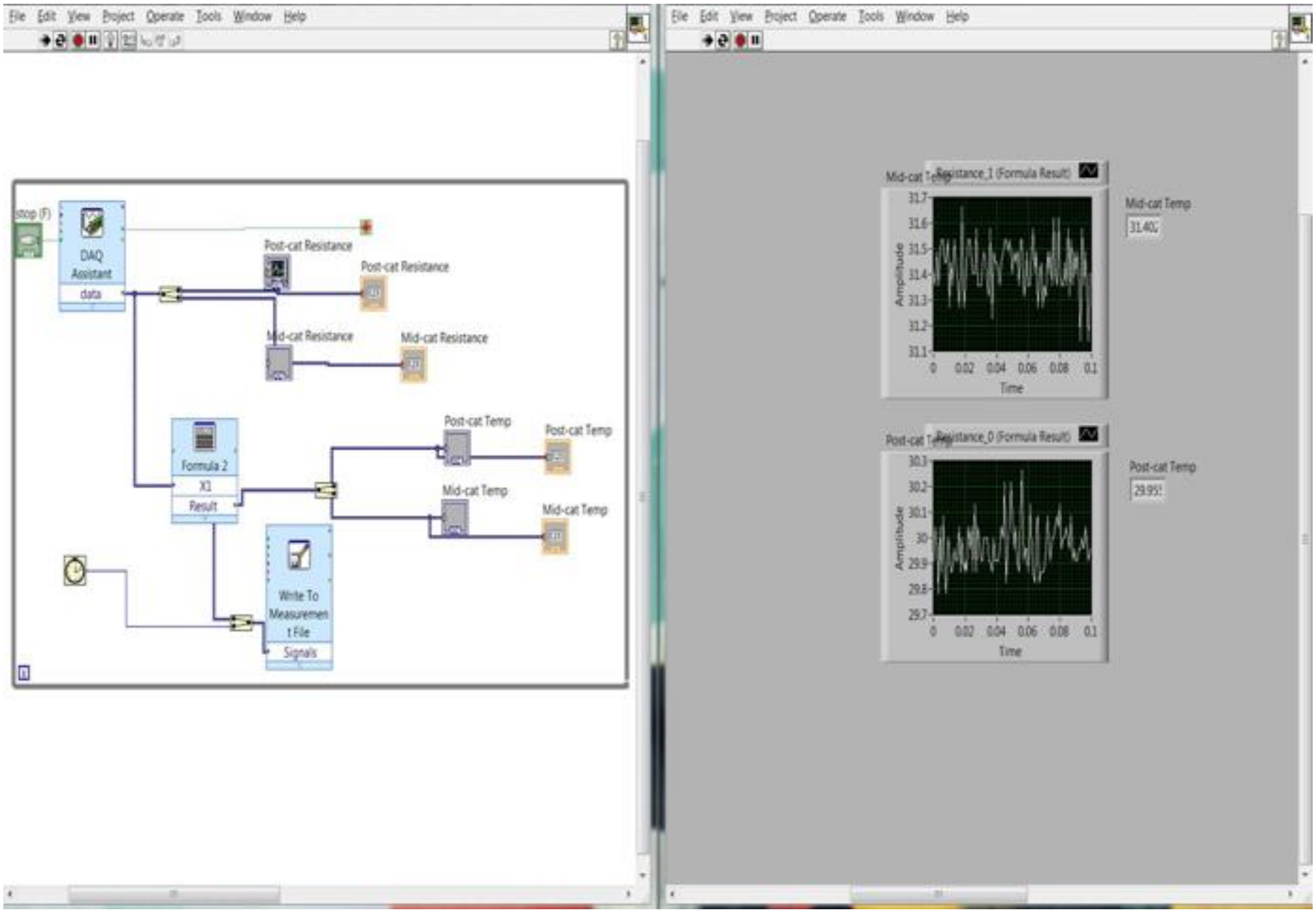

Figure 6 LabVIEW Temperature Data Acquisition Bench

In Figure 7, it showed a user interface of the LabVIEW setup for the acquisition of emissions data. The front panel of the emissions data acquisition could monitor the instantaneous data of CO, CO2, O2, THC and NOx. The primary emissions gas this research looked at were CO, THC and NOx. In the emissions charts, this LabVIEW has both CO (Low) and CO (High). The value of CO (High) would be used since the emissions of CO would reach its saturation limit if the reading was above 5000 ppm. Once the emissions testing was completed, two files would be generated to tell the emissions history before and after the EHC. The emissions of three primary emissions before the EHC should stay the same but the emissions after the EHC would drop at the same level as the emissions level before the EHC to a much lower level.

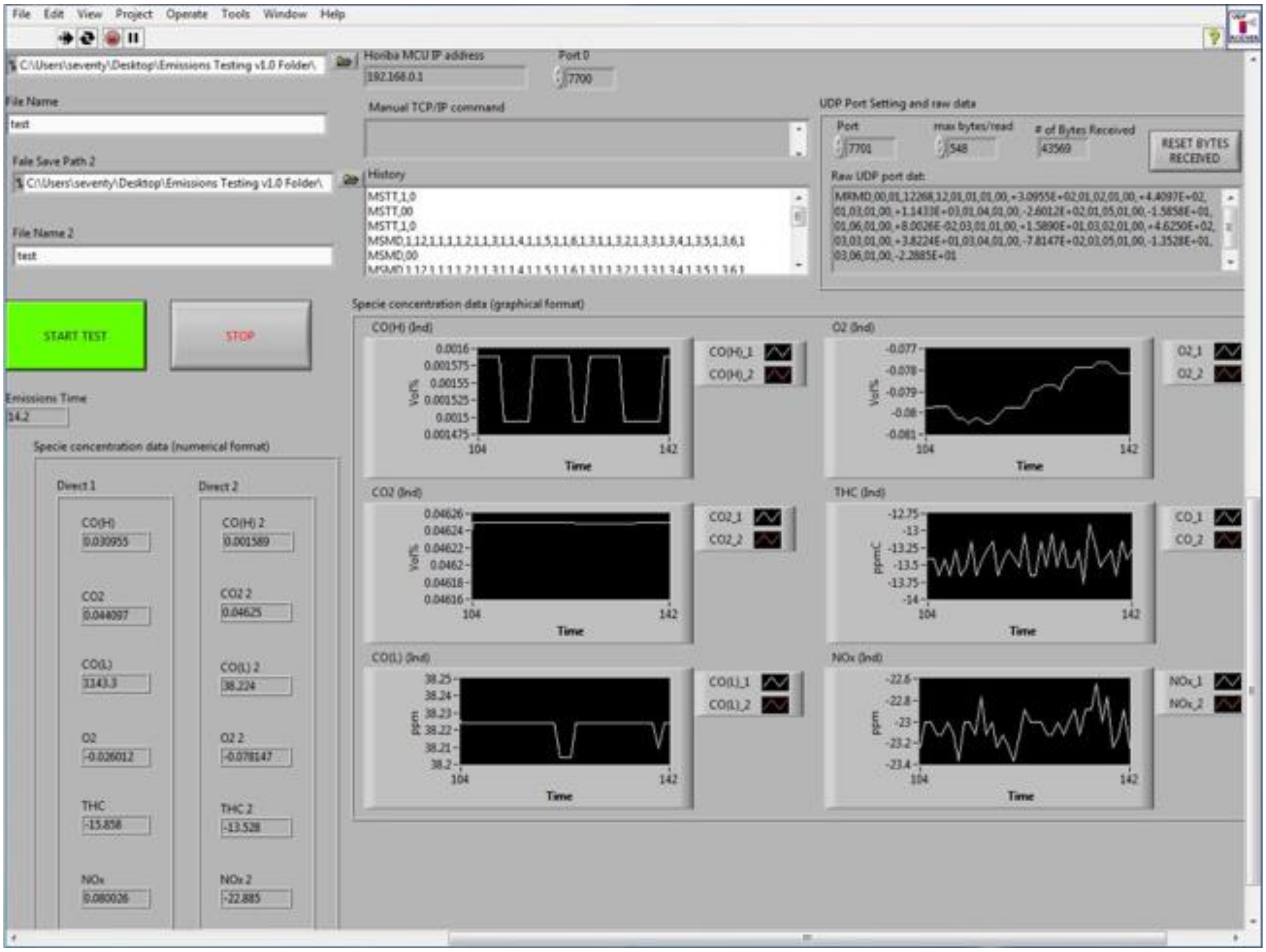

Figure 7 LabVIEW Emissions Data Acquisition Bench

2.3 *Electronical Sensors*

2.3.1 *Oxygen sensors*

The oxygen sensors are installed on the exhaust system on both testing bench and actual vehicles. As it mentioned in the introduction chapter, the vehicles need to be in close-loop control while we heat up the EHC. The feedback signal that pushes the engine into close-loop control is the oxygen sensors. The supervisory controller can calculate how much fuel it needs to inject based on first a few iterations of air/fuel ratio. To secure the oxygen sensors onto EHCs permanently in a durable way, two female nuts will be welded onto pre-cat and post-cat locations just before and after the EHC. Then, the oxygen sensors are connected to the female nuts on the EHC.

2.3.2 Resistance Temperature sensors

The installation of the RTD was achieved by welding the female nuts of compression fitting onto the EHC, then the male bolts of compression fitting that fixed the RTD were connected to the female nuts. By doing so, the RTDs were permanently installed onto the EHC with the high tolerance of vibration absorption.

The temperature signal is the key factor to determine if the EHC receives sufficient thermal energy to heat up above the light-off temperature. To better understand the thermal and chemical characteristics of the EHC, two RTDs will be used on the testing bench. They are installed at mid-cat and post-cat location. As Figure 8 showed, RTD at mid-cat location was used as the control signal to indicate the light-off temperature of the EHC. The post-cat RTDs was used to understand the temperature of the EHC during the heating phase and normal engine operating phase. Once the thermal and chemical characteristics of the EHC was determined through the experimental testing, only one RTD would be installed onto EHC at mid-cat location with the consideration of light weight, cost and reduction of vehicle control complexity. The mid-cat RTD was installed at the 1/3 position of the EHC cylinder from the engine side. This temperature signal was used as the indicator to allow the close-loop control for the EHC heating.

Figure 8 RTD (Resistance Temperature Detector)

For testing setup, a RTD circuit was created on the breadboard for the data collecting purpose. In Figure 9, two resistances with the values of 2.2K were wired in series with two RTDs to protect any firing hazards.

Both RTDs were connected to the plus and minus analog inputs pins on the NI myDAQ. Two orange wires showed were power and ground wires from the solid-state relay. They were connected to the analog output and digital ground on the NI myDAQ since the ground pins were shared for both digital and analog pins. The NI myDAQ was connected to the data acquisition computer with the setup of the LabVIEW software through the USB cable to collect the real-time temperature and emissions data.

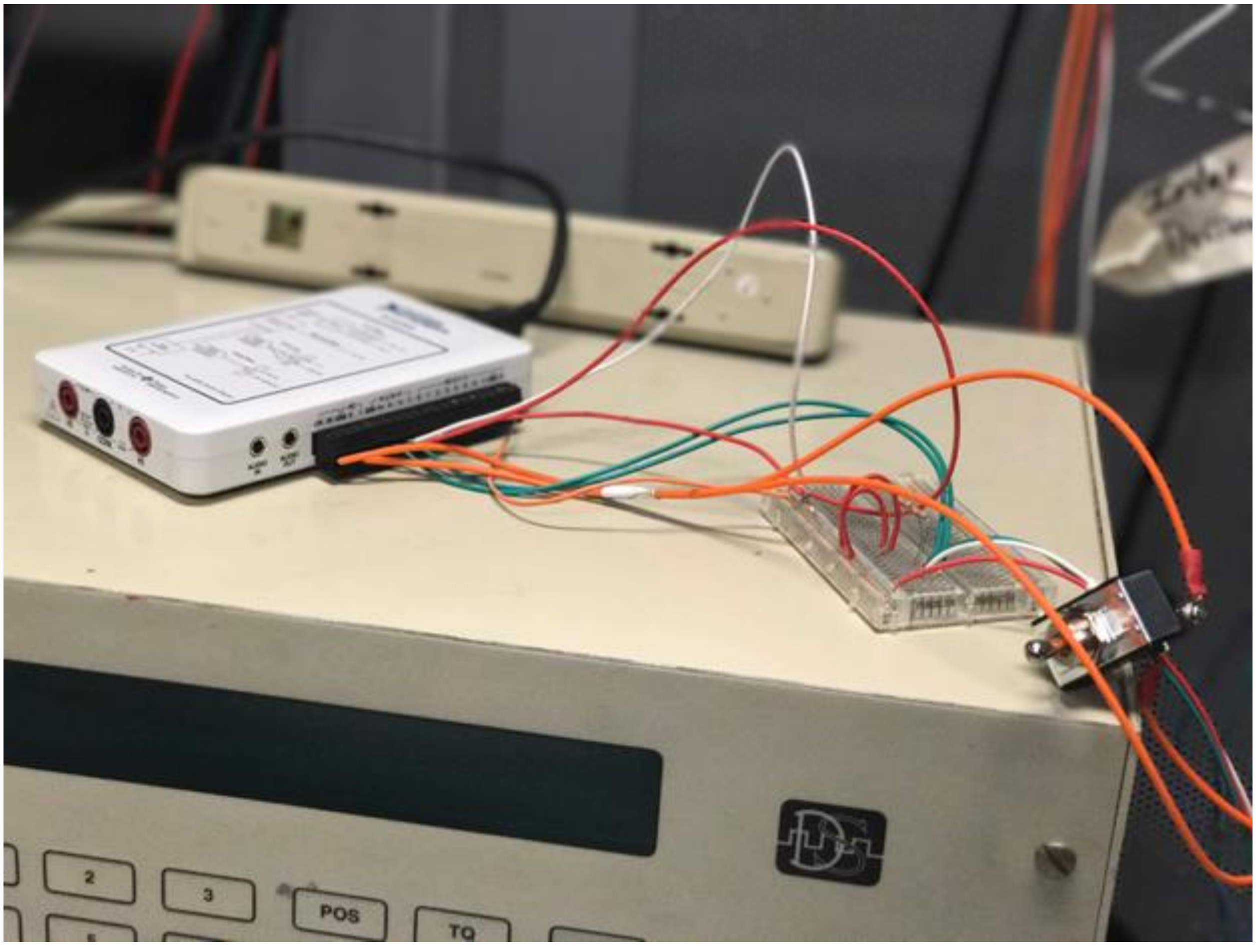

Figure 9 Circuit of RTD and Solid-State Relay

2.3.3 Exhaust Analyzer

In the competition, the emissions would be graded as one of most important parts of competition. The emission data will be collected before and after the EHC through the emission collecting pipes that are installed at the same axial location of the oxygen sensors. The concentrations of emissions of these three gases would be recorded in the units of ppm with the EHC heating. The baseline emissions data without the EHC heating since the engine cold-start would also be recorded. In this research, a wide range of testing with different light-off temperature would be conducted to collect the emissions data before and after the EHC. By doing so, the control strategy can be tuned to meet the requirements of emissions reduction with lowest energy consumption and shortest heating time. The emissions conversion efficiency of three emission gases will be calculated respectively. Hence, A bar chart would be created to compare the emissions conversion efficiencies of three emission gases with the baseline emissions data for a fixed time range. The comparison would be used to show the improvement of conversion efficiencies with the EHC heating. In Figure 10 and Figure 11, they showed a picture of emission analyzer and monitor view of emissions data.

Figure 10 Exhaust Analyzer

Figure 11 Monitor View of Emissions Data

2.3.4 Power Supply

On the vehicle, a voltage of 13.4 volts was used as the standard voltage on the vehicle for the EHC heating and operation of other electronical components. The vehicle battery would supply around 60 amperes to the EHC during heating phase. As a result, the voltage would potential drop instantaneously below 12 volts if the current drawing was at a high demand continuously. Hence, the supervisory controller of the vehicle would lose the control signals because most sensors and control modules required an operation voltage above 12 volts. To avoid the vehicle blackout, the rest of current would come from the DC-DC converter. The DC-DC converter converted the high-voltage power from high-voltage battery to 13.4 volts' power. Two power sources of DC-DC converter and vehicle battery would be connected in parallel on the vehicle. The total current of 154 amperes will be supplied to the EHC for approximate 60 seconds.

On the dynamometer testing setup, as it showed in the Figure 12 and Figure 13, a AC-DC converter and external battery were used to simulate the power supply on the vehicles. With the consideration of protecting battery life time and simulating the same power supply approach on the vehicle, the team used a AC-DC converter whose cable could handle a maximal current of 60 amperes to supply the power to the EHC heating in parallel with external battery. A total of 154 amperes will be supplied to the EHC from these two power sources on the dynamometer setup.

Figure 12 AC-DC Converter

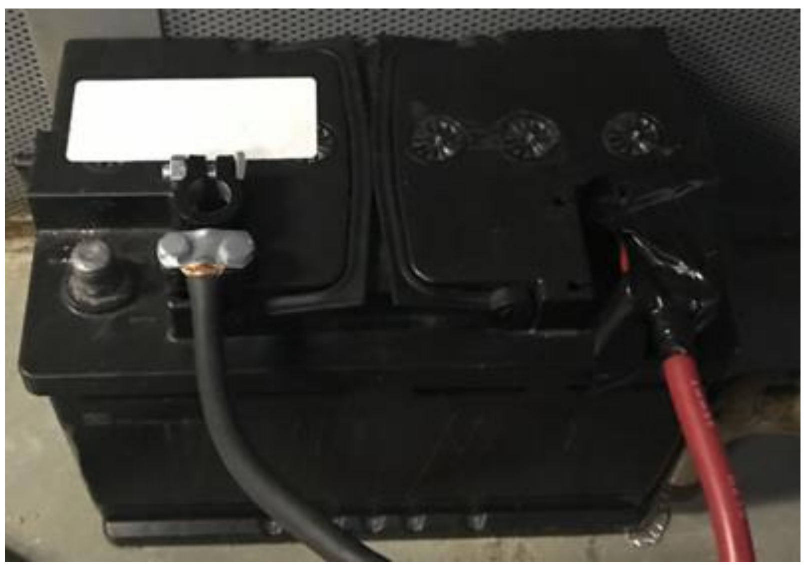

Figure 13 External Battery Power Supply

2.3.5 Solid-State Relay and ECU Voltage Command

As the thesis introduces before, both external battery on the dynamometer setup and battery on the vehicle experience an instantaneous voltage drop if the current drawing is too much. This voltage drop results in an electronical system blackout for most controllers and control modules. To avoid the hazards caused by the electronical system blackout, a ECU command was used to increase the voltage of DC-DC converter if the voltage dropped too much on the battery. As it showed in

Figure 14, a solid-state relay would be used to turn on and off the power supply to the EHC. If the voltage drop occurred on the vehicle battery, the supervisory controller would increase the voltage of DC-DC converter to keep the vehicle voltage constantly above 13.4 volts. On the dyno and vehicle circuit setups, a 150-ampere resistance is connected in series with the solid-state relay as a secure protection.

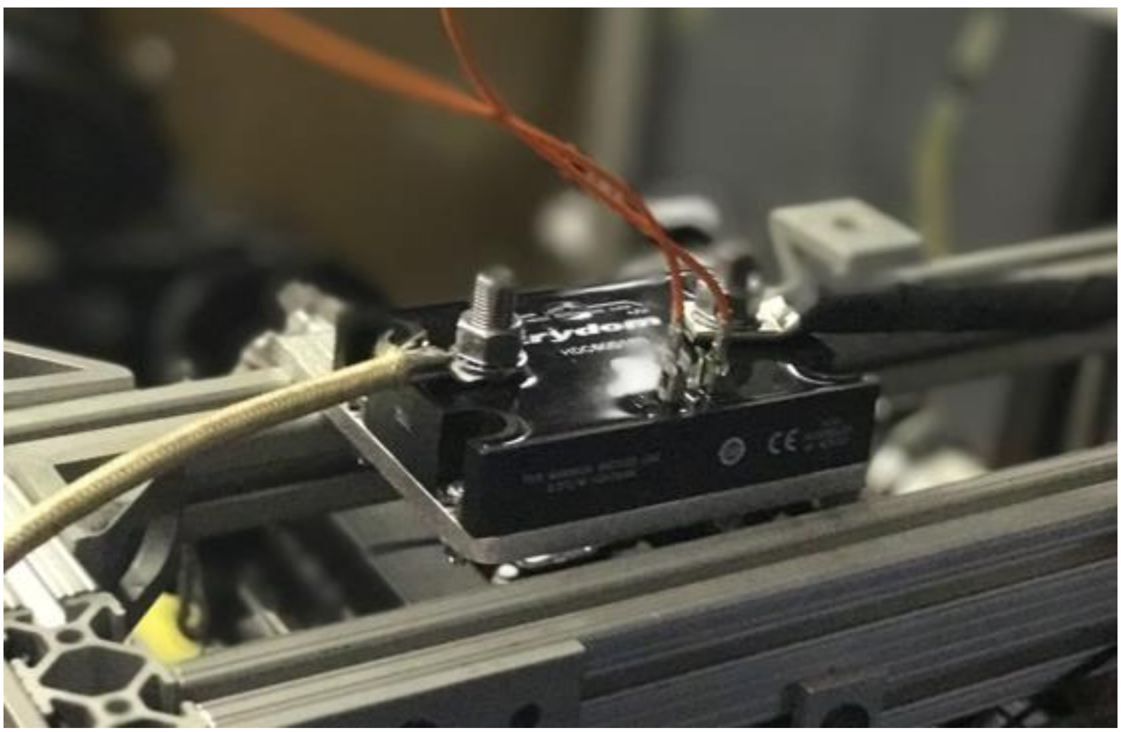

Figure 14 Solid-State Relay

3 Experimental Testing and Results

3.1 Air Flow Rate Testing

In this research, a constant input of air mass flow rate was required during the EHC heating phase to transfer the heat from the heating elements to the main body of the EHC. Previously, on the EcoCAR 2 competition team, a secondary air pump device was installed between the exhaust collector and the pre-CAT location. The external air pump device adds extra weight, complexity and cost to the vehicle. To avoid these drawbacks in the previous EcoCAR vehicle, this research proposes to get the same amount of air mass flow rate from the engine exhaust by using the BAS to crank the engine in electrical mode before firing engine.

Based on the experimental results from the EcoCAR 2, the design space for the air mass flow rate is from 2 grams/second to 6 grams/second. However, based on the experimental testing, we could see that if the air mass flow rate that was lower than 4 grams/second, it took longer to heat up the EHC because the air speed was not higher enough to transfer the heat quickly. If the air mass flow rate was greater than 5 grams/second, the mass air flow rate was too high that will exert a cooling effect onto the EHC instead. Hence, the optimal range of air flow rate was between 4 grams/second and 5 grams/second. To get the same amount of air flow rate from the engine exhaust, the engine must be cranked at certain RPMs to get corresponding air mass flow rate.

In this research, the air mass flow rate testing was completed to characterize the relationship between air mass flow rate and engine RPMs in two conditions. The first air mass flow rate testing was completed when the throttle position was fully closed. In addition to this, the second air mass flow rate testing was completed when the throttle position was fully opened. To optimize the electrical power consumption, the fully opened throttle position could increase the air from the air intake which resulted in a lower engine cranking RPM. In the control strategy, the fully closed throttle position would be used as the backup solution to produce the same amount of air mass flow rate.

Both air mass flow rate testing was accomplished on the dynamometer, in Figure 15, it showed that the engine was mounted on the dynamometer. From the consideration of the energy consumption and consumer acceptability, three criteria were evaluated to determine what engine RPM should the control strategy use on the vehicle to get the desired air mass flow rate. They included the energy consumption, vibration and noise. To save the electrical energy, a lower RPM was preferred in this control strategy. However, a lower RPM would cause more vibration and noise because the engine experience its first resonant frequency between 400 and 500 RPMs. With the consideration of evaluation criteria such as vibration and noise, a series of engine RPMs was tested out in two conditions described above to characterize the air mass flow rate of the engine.

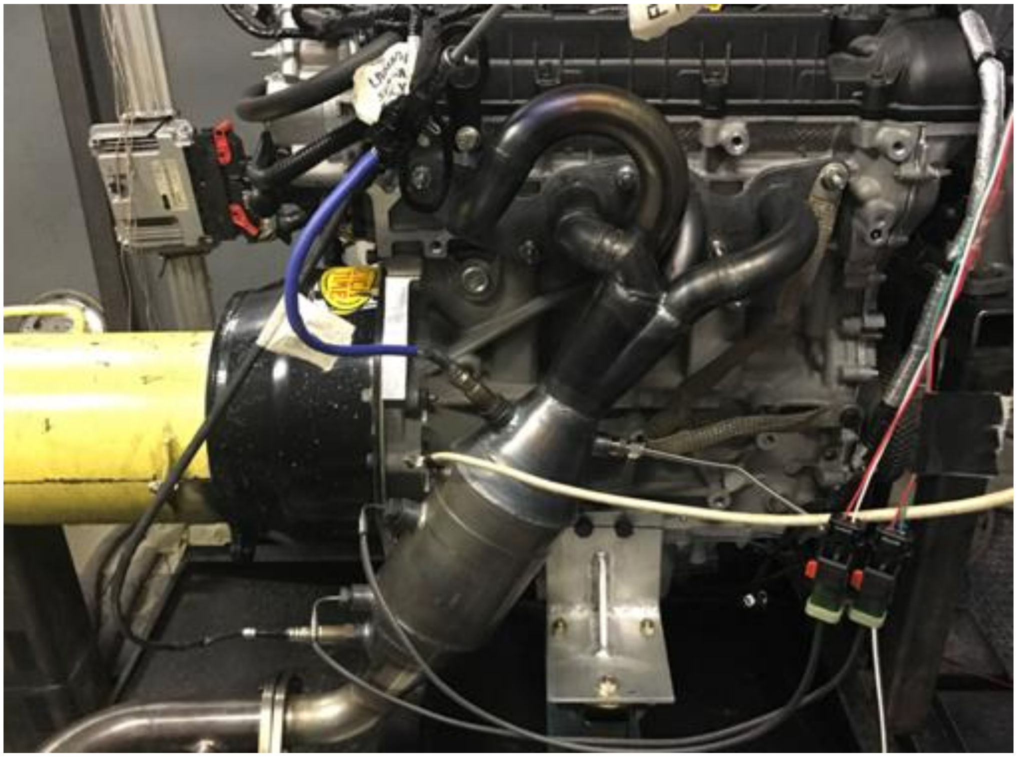

Figure 15 Engine Dynamometer Setup

In Figure 16, it showed characteristics of engine air mass flow rate as the engine cranking speeds changed from 280 RPMs to 760 RPMs when the throttle position was fully closed. The 500 RPMs was the desired engine speed that could run the engine smoothly without any concerns of harmful vibration. After the testing, the experimental data indicated that 290 RPMs could produce an average mass air flow rate at 2.569 grams/second. This mass air flow rate was treated as the starting point to sweep the engine speed up to where it could produce 6 grams/second. As the experimental results showed, the engine needs 600 RPMs to produce 6 grams/second mass air flow rate. This testing was conducted up to 760 RPMs for the sake of testing quality. As the engine speeds operated at 420 RPMs, the air mass flow rate from the engine exhaust was approximately 4 grams/second. Then, the RPM increments changed from 20 RPMs to 10 RPMs since the air mass flow rate was within the interests range. The testing results showed that the air mass flow rate increased from 4 grams/second to 6 grams/second from 420 RPMs to 600 RPMs. To make sure the mass air flow rate is stable during the EHC pre-heating phase, the team decided to use 4.643 grams/second at 510 RPMs for the control strategy development. This engine speed also run the engine smoothly if take the customer acceptability into consideration.

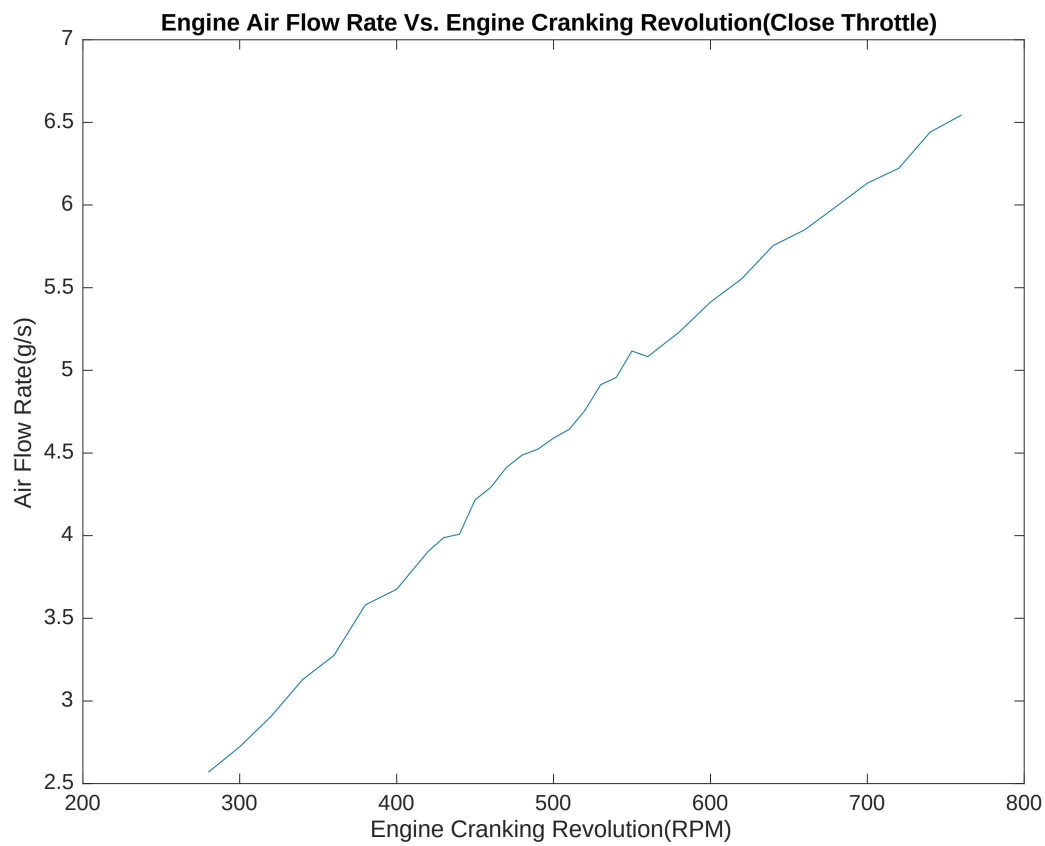

Figure 16 Engine Air Flow Rate Mapping to Engine Speed in Closed Throttle Condition

In Figure 17, characteristics of engine air mass flow rate as the engine cranking speeds changed from 210 RPMs to 760 RPMs when the throttle position is fully opened. The engine speed swept from 210 RPMs to 270 with an increment of 20 RPMs since the air mass flow rate was below 4 grams/second. When engine speed reached 290, the cranking engine could produce an air mass flow rate of 4.457 grams/second. From the engine speed of 290, the RPMs increments changed from 20 RPMs to 10 RPMs since the air mass flow rate was within the interest range. The testing was completed until the engine speed reached the 550 RPMs. As Figure 17 displayed, the air mass flow rate would bounce around between 290 RPMs to 550 RPMs because of the air propagation from the air intake. To produce a stable air mass flow rate from the engine exhaust when the throttle was fully opened, the team decided to crank the engine at 290 RPMs. This engine RPMs also met the criteria of decreasing power consumption and reducing the engine vibration and noise.

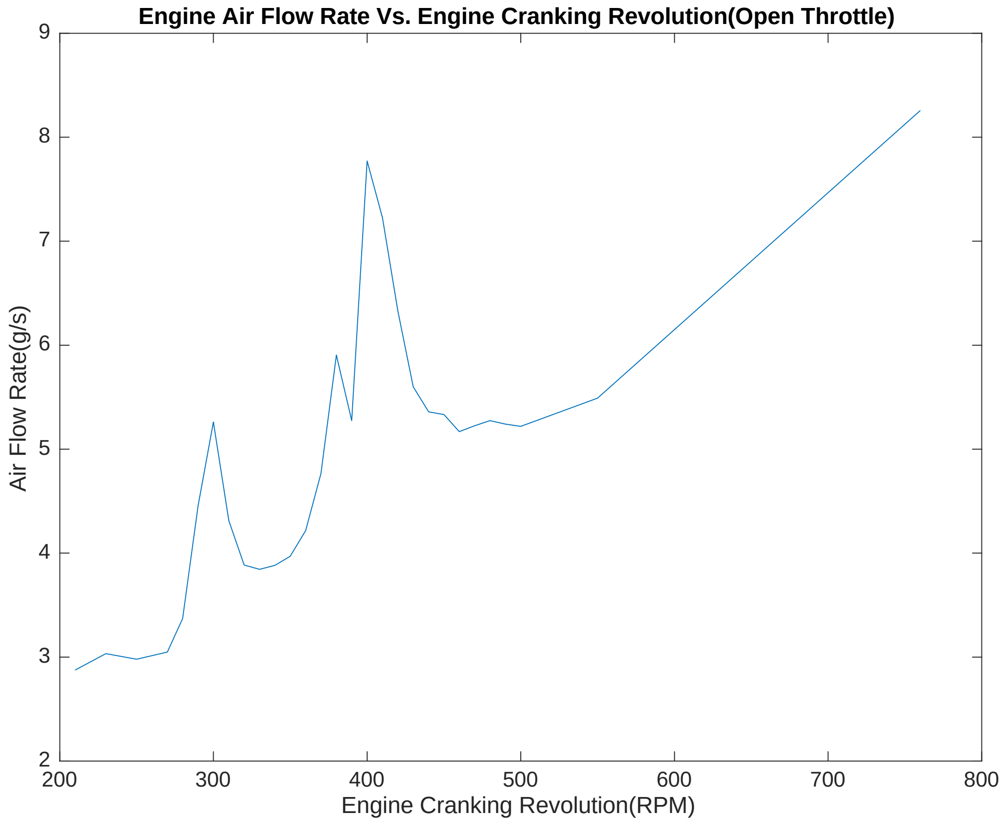

Figure 17 Engine Air Flow Rate Mapping to Engine Speed in Opened Throttle Condition

In the actual implementation of the control strategy, the engine would be cranked by the BAS at the speed of 290 RPMs with the fully opened throttle position. Once the ECU signal detected that the air mass flow rate was developed above 4 grams/second, the control strategy would send the commands to heat up EHC. If the air mass flow rate could not be developed above 4 grams/second with the condition of fully opened throttle position, the control strategy would crank the engine at 510 RPMs with the condition of fully closed throttle position as the backup solution.

3.2 Thermal and Chemical Characteristics Testing of EHC

In this section, it discussed the experimental results of emissions baseline testing and the emissions testing at different light-off temperature. The purposes of doing this testing were to find an appropriate light-off temperature as the control criteria for the control strategy and to investigate the relationship between the emission conversion efficiencies and the light-off temperature. The emissions gases including NOx, THC and CO, would be collected to calculate the emissions conversion efficiencies. Eventually, the conversion efficiencies of three primary emissions would be used to compare with the conversion efficiencies of baseline emissions data in a fixed time span.

As Table 3 showed, the testing was conducted with a constant air mass flow rate and full electrical load condition. The light-off temperature was the only independent variable in this testing. Based on the specification sheet from the EHC supplier, Emitec, the desired light-off temperature of the EHC that the EcoCAR 3 team used in this project is 310 $°C$. The emissions testing was conducted from the light-off temperature at 270 to 350 $°C$ to understand how does the light-off temperature affect the emission conversion efficiencies.

Table 3 Thermal Testing at Different Light-Off Temperature

Light-Off Temperature©	Test	Power(W)	Air Flow (g/s)
270	1	2200	6.8
290	2	2200	6.8
310	3	2200	6.8
330	4	2200	6.8
350	5	2200	6.8

Before heating up the EHC at different light-off temperatures, the baseline emissions testing was conducted first to understand the baseline conversion efficiencies of three primary emissions. After the baseline emissions testing, the testing results indicated that the emissions after the EHC started to drop greatly after 70 seconds. As a result, a fixed time length of 70 seconds was used to calculate the conversion efficiencies for all of testing at different light-off temperature.

The conversion efficiency was calculated with the equation below.

$$\eta = 1 - \frac{Trapz\left(\frac{Emission_{out}}{t}\right)}{Trapz\left(\frac{Emission_{in}}{t}\right)}$$

As Figure 18 showed, the history of emission THC at 270 °$\boldsymbol{C}$ was recorded at pre-CAT and post-CAT locations. The area under the blue line for a fixed time length of 70 seconds would be used to calculate the integration of emissions in. Then, the integration would be divided by the fixed time length of 70 seconds to calculate the average value of the emission of THC before the EHC. The same integration would be used to calculate the average value of the emission of THC after the EHC. The same fixed time length was applied for other two emissions of NOx and CO from light-off temperature at 270 °$\boldsymbol{C}$ to light-off temperature at 350 °$\boldsymbol{C}$. The entire calculations were conducted in the MATLAB. The *trapz* was the MATLAB command to calculate the integration with the trapezoid shape.

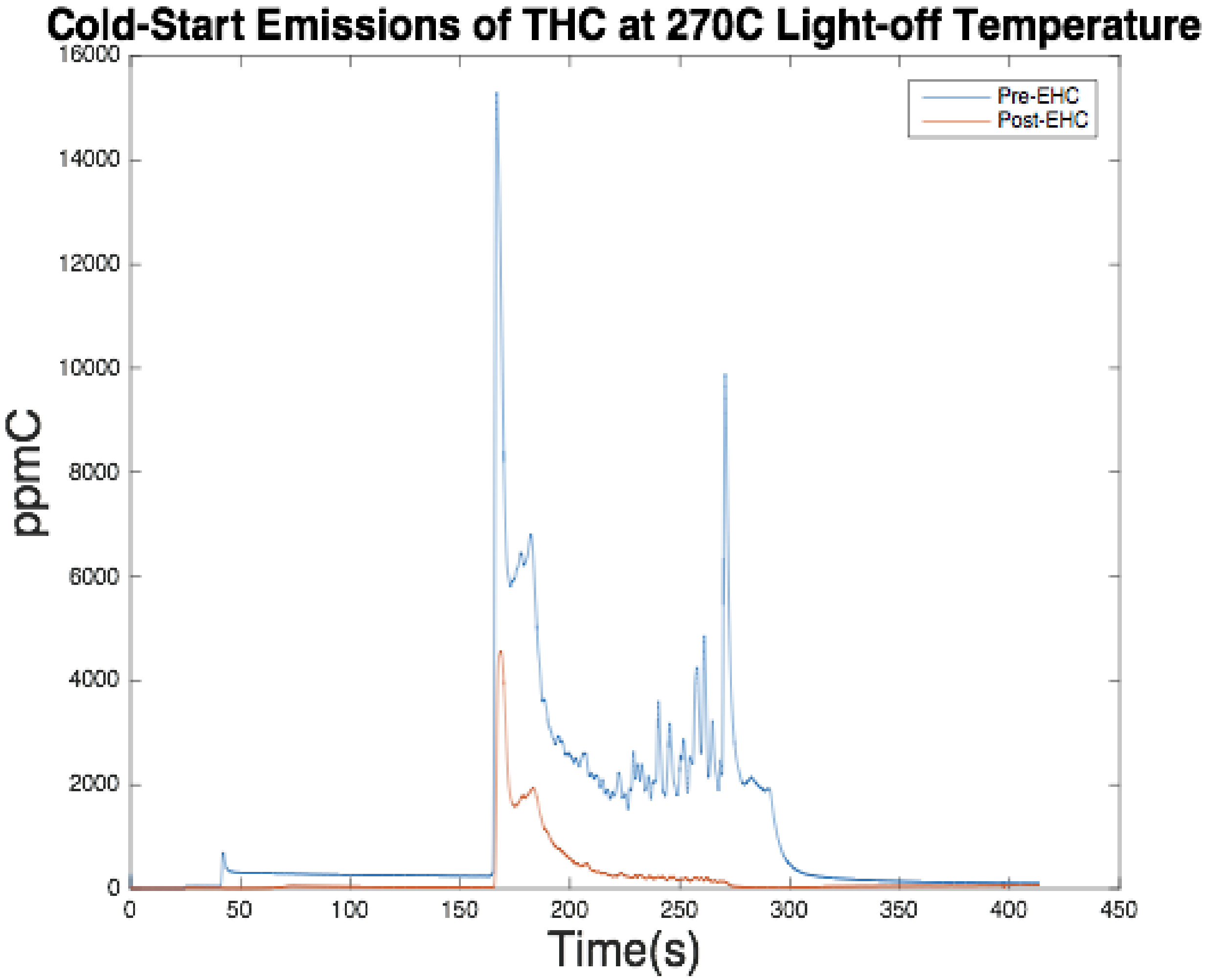

Figure 18 Emission History of THC at 270C Light-off Temperature

In Figure 19, the baseline NOx conversion efficiency was tested from engine cold-start without EHC heating. It had 29.06% conversion efficiency at baseline testing whereas the highest conversion efficiency at 270 $°C$ was 84.25%. The biggest improvement was 55.19% thanks to the EHC heating. Compared the conversion efficiency at 270 $°C$ to the conversion efficiency at 350 $°C$, the conversion efficiency decreased by 3.16%. From the plot, the conversion efficiency was 88.80% at light-off temperature of 290 $°C$ and was 87.12% at light-off temperature of 310 $°C$. This difference with other three light-off temperature was caused by conducting the experiments in the different day. The first testing was conducted at 270, 310, 350 $°C$. Then, additional testing was conducted at 290 and 330 $°C$. Although the magnitudes of the conversion efficiencies in two different testing days were different, the magnitude of discrepancy was within 5%. This difference between two testing date was caused by the experimental variation that could not controlled on the engine dyno setting. Since the conversion efficiencies at 270 $°C$ had a big improvement compared to the baseline conversion efficiency, it had been determined that this experimental variation was acceptable unless the variation was larger than 5% if the increment between light-off temperature was still 10 $°C$. The same situation would apply for the conversion efficiency bar chart of other two emissions gases: THC and CO.

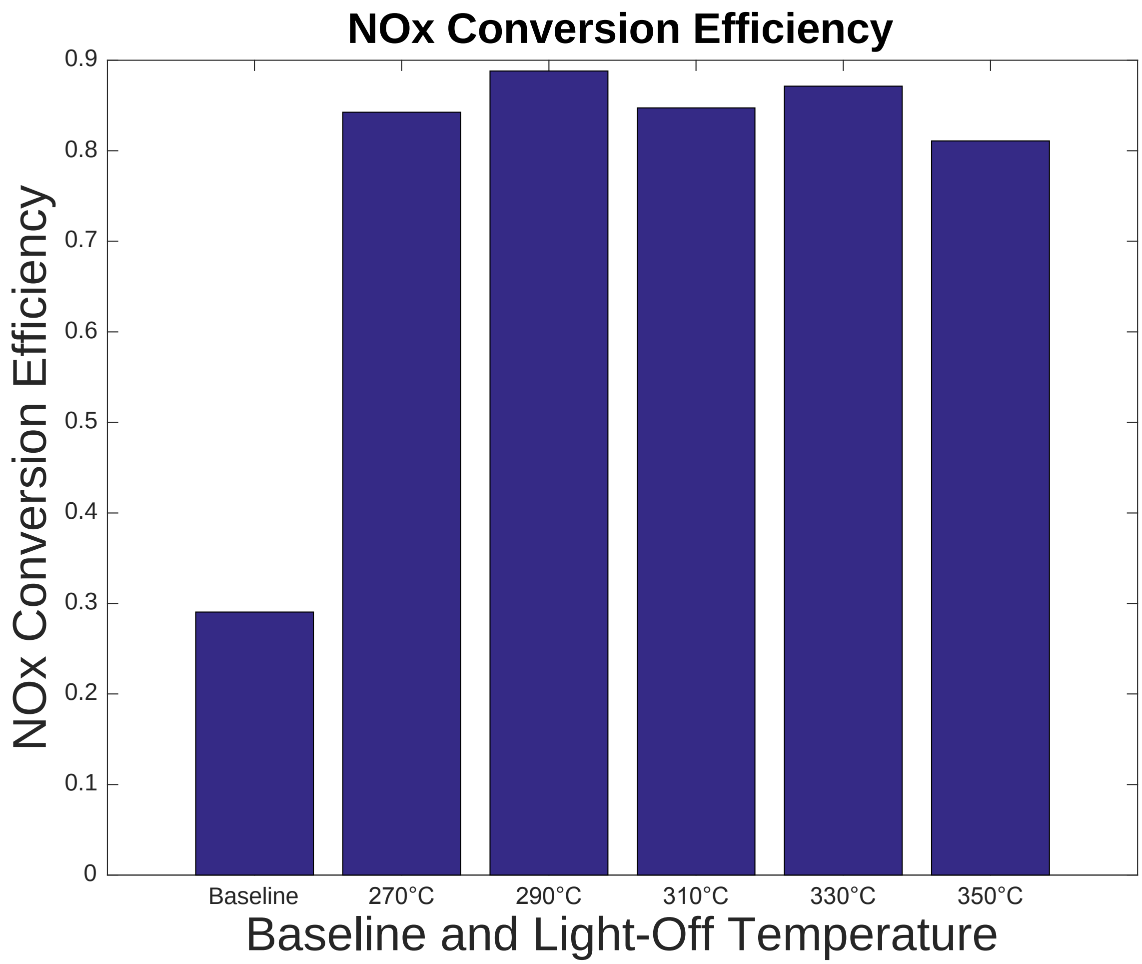

Figure 19 NOx Conversion Efficiency at Various Light-Off Temperature

In Figure 20, the baseline THC conversion efficiency was tested from engine cold-start without EHC heating. It had 7.52% conversion efficiency at baseline testing whereas the highest conversion efficiency at 270 $°C$ was 73.32%. The biggest improvement was 65.8% thanks to the EHC heating. The conversion efficiency at 270 $°C$ was only 0.26% higher than the conversion efficiency at 350 $°C$. The discrepancy of conversion efficiency between 270 $°C$ and 290 $°C$ was 7.8%. This difference was within 10% which was considered acceptable between two different light-off temperatures.

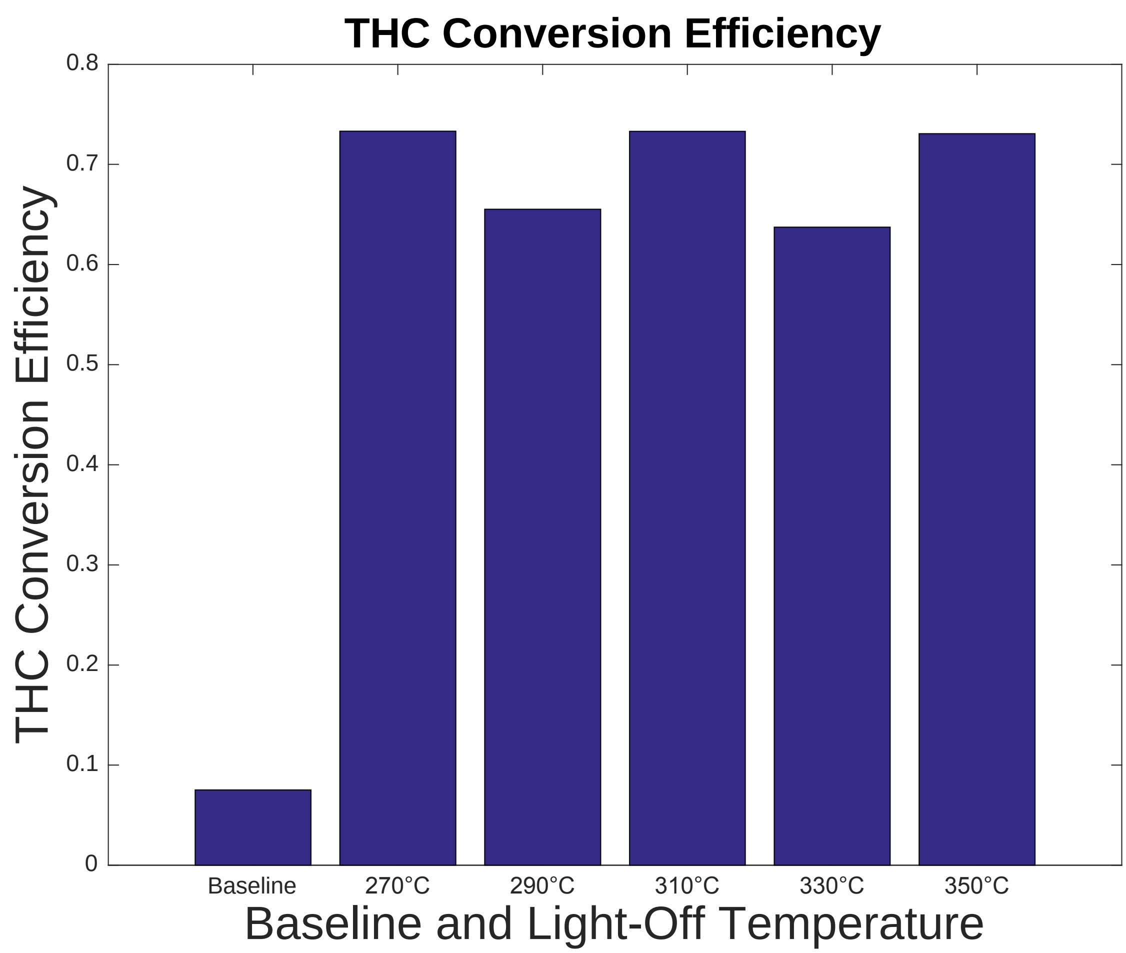

Figure 20 THC Conversion Efficiency at Various Light-Off Temperatures

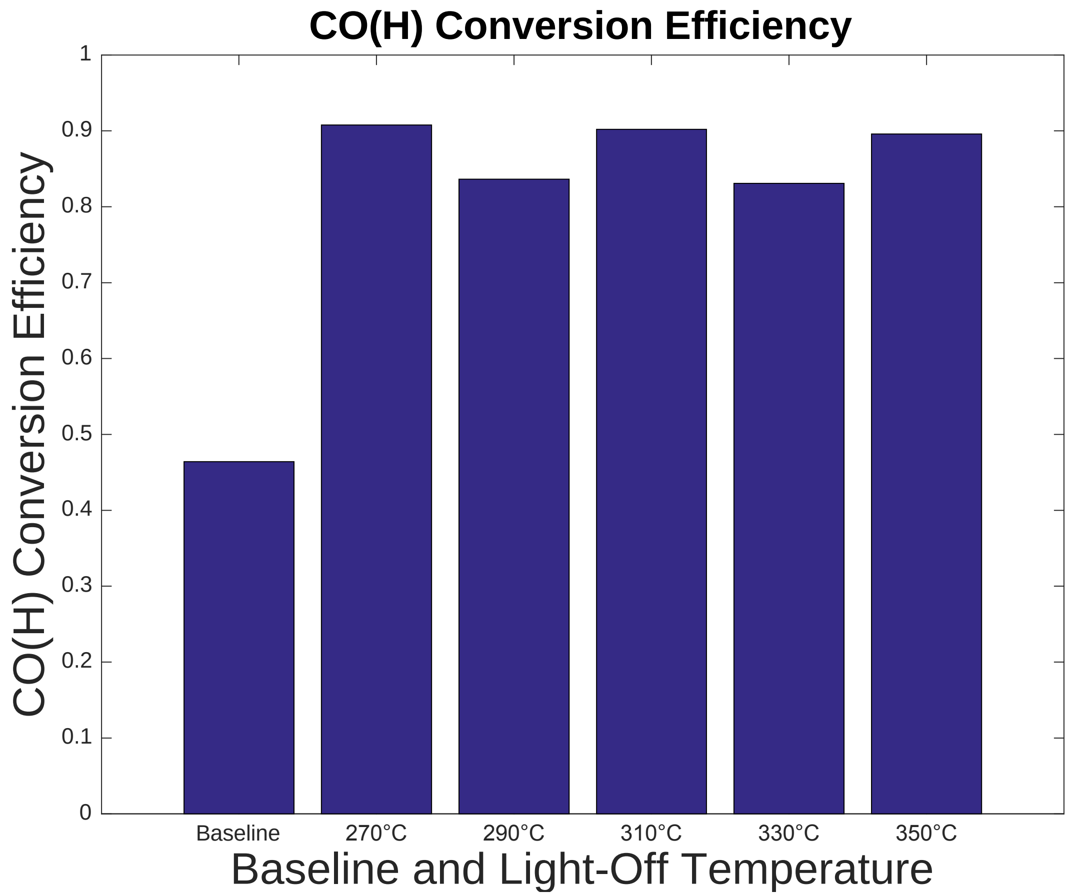

Figure 21 CO Conversion Efficiency at Various Light-Off Temperature

In Figure 21, it could be seen that as the light-off temperature increased, the conversion efficiencies of CO decreased slightly. The baseline CO conversion efficiency was tested from engine cold-start without EHC heating. It had 46.4% conversion efficiency at baseline testing whereas the highest conversion efficiency at 270 °$\boldsymbol{C}$ was 90.78%. The biggest improvement was 44.38% because of the EHC heating. The conversion efficiency at 270 °$\boldsymbol{C}$ almost the same as the conversion efficiency at 350 °$\boldsymbol{C}$. The discrepancy of conversion efficiency between 270 °$\boldsymbol{C}$ and 290 °$\boldsymbol{C}$ was 7.16%. This difference was within 10% which was considered acceptable between two different light-off temperatures.

A few things were considered to determine what light-off temperature would be selected for the control strategy. They include the time to light-off temperature, the energy consumption and the emission conversion efficiencies of three primary emissions gas: THC, CO and NOx. It could be seen that the light-off temperature at 270 $°C$ was the optimal temperature based on the evaluation of the criteria mentioned above. Since the light-off temperature at 270 $°C$ would take least amount of energy and shortest time for the EHC to reach. In addition to these two factors, these three figures concluded that the conversion efficiencies of three primary emissions gases were highest at 270 $°C$. This further confirmed the light-off temperature at 270 $°C$ would be used for the control strategy.

3.3 Engine Firing RPM Testing

In this section, it will discuss the engine firing RPM testing. The purpose of this testing was to find an engine firing RPM that could start the engine without hurting the emissions reduction of engine cold-start. In most cases, if the engine firing RPM was lower than the idling RPMs, the ECU would send the comments to inject more fuels to bring the engine RPM back above the idling speed. This additional fuel injection could produce more emissions when the engine started for the first time. To avoid the additional injection of the fuels and reduce the emission during the engine cold-start, the engine firing RPM must be above idling RPMs.

There are three additional factors that need to be considered when evaluating the engine firing RPMs. They include the engine vibration, engine noise and throttle position. Figure 22, the raw data of engine speed at different levels of RPMs indicated that the engine would have smaller engine vibration as the RPMs increased.

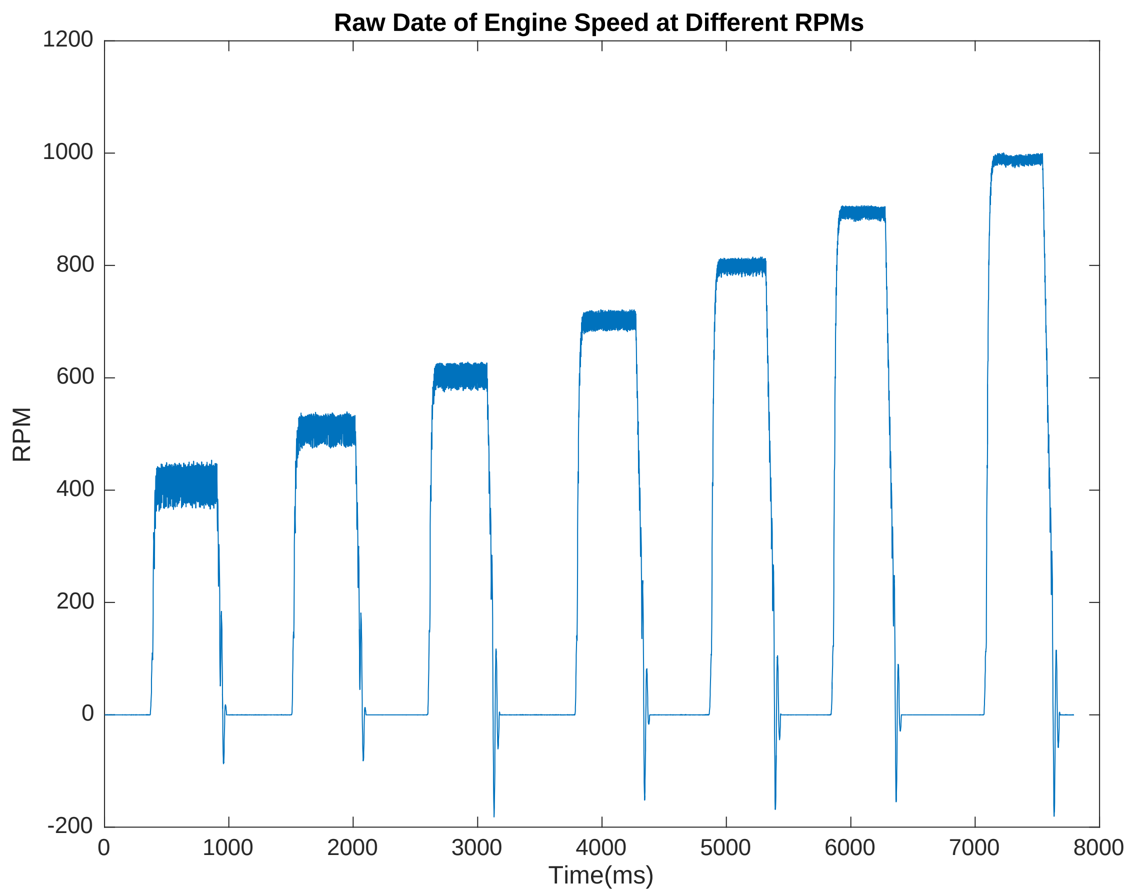

Figure 22 Engine Speed Variation at Different RPMs

In this research, it could see that the engine would reach the steady state after 12 seconds. The steady state RPMs was the idling RPMs without any fuel injection and throttle position change. For the emission reduction, the engine firing RPMs need to be above 780 RPMs to avoid hurting the emissions reduction after engine cold-start.

As it could be seen in Figure 23, the average engine speed at 800 and 900 RPMs were close to the actual RPMs set on the dynamometer. Based on the criteria of engine vibration, this amount of engine vibration was acceptable for our control strategy development.

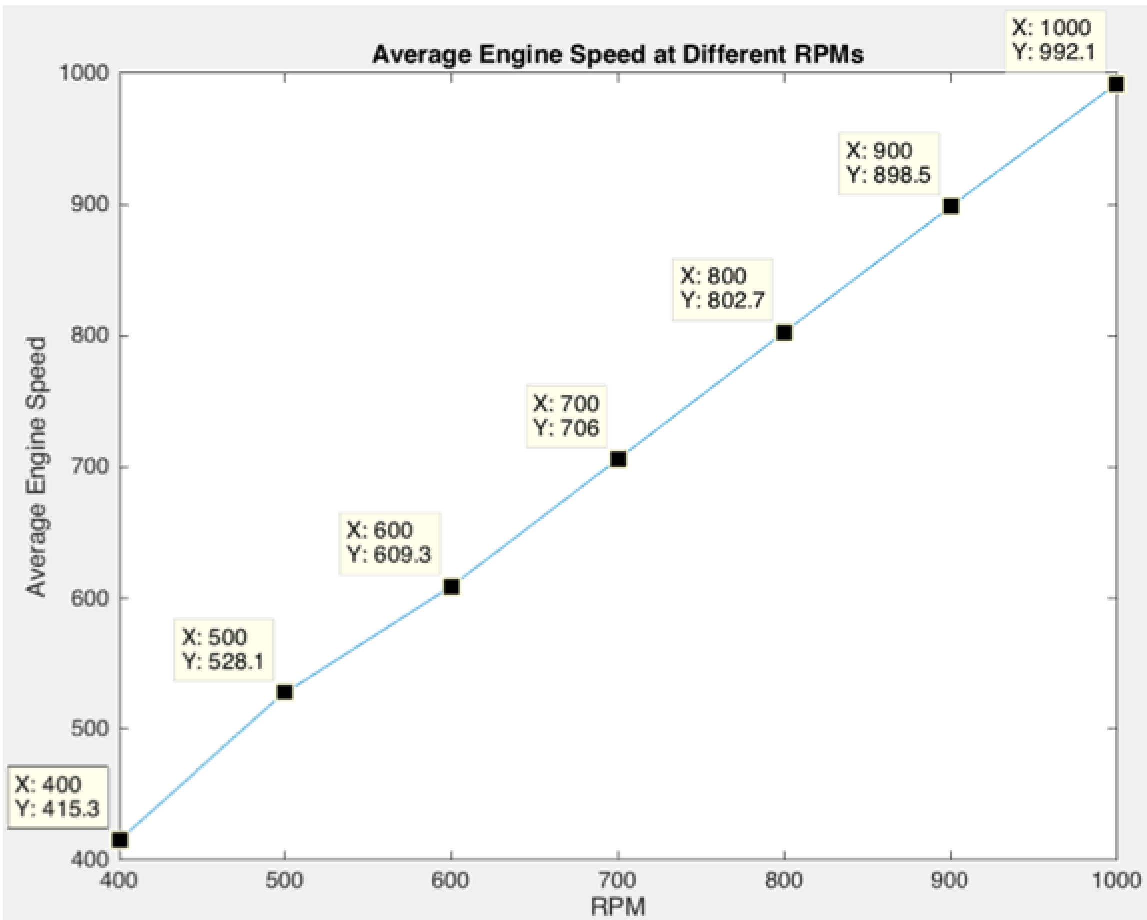

Figure 23 Average Engine Speed at Different RPMs

In addition to that, Figure 24 showed that the standard deviation of the engine vibration became smaller as the engine speed increased. When the engine speed reached 800 RPMs, the standard deviations of the engine speeds were within 10.

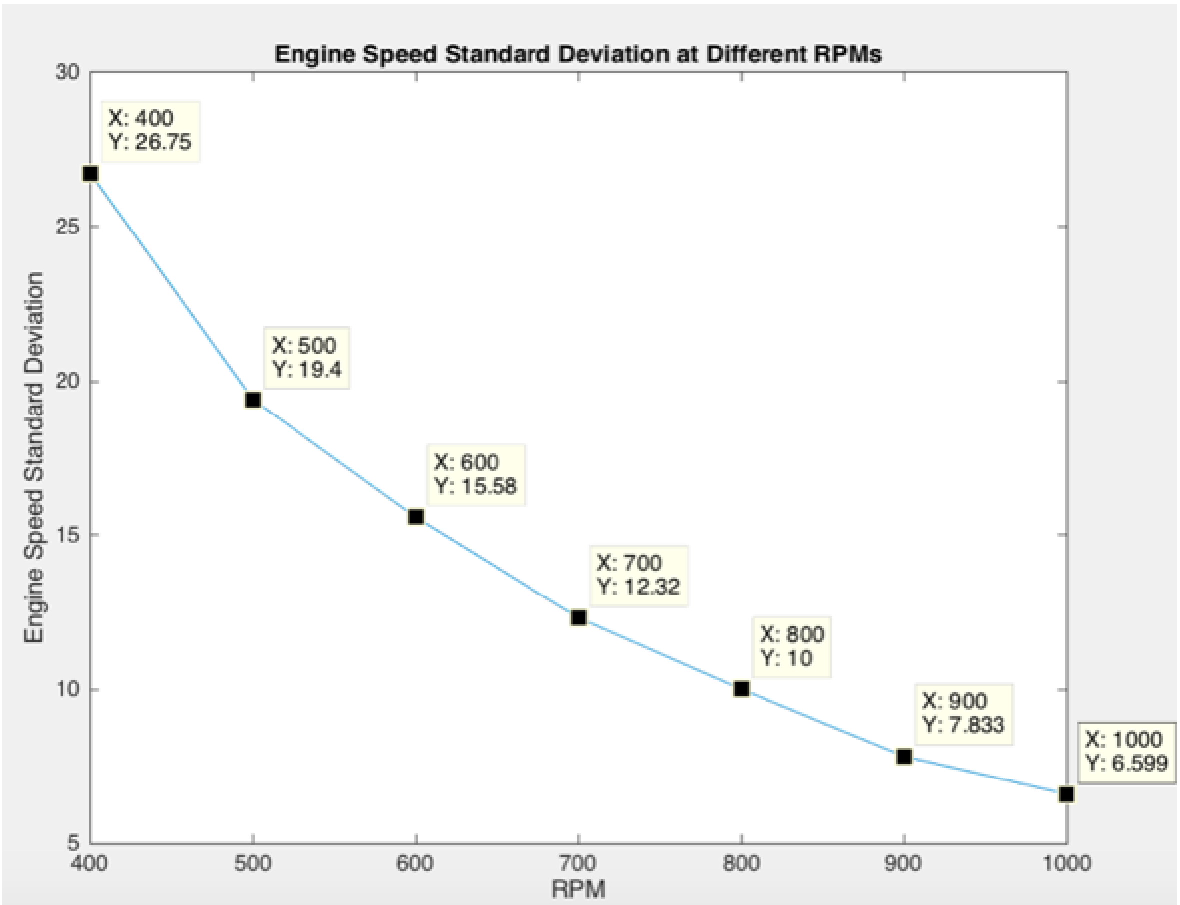

Figure 24 Engine Speed Standard Deviation at Different RPMs

Besides, the engine speeds were also investigated at the same engine speeds with different throttle positions. The purpose of doing this research was to understand if the variation of throttle position would affect the engine speed vibration since the control strategy required a signal to control the throttle position.

In Figure 25, it could be seen that the raw data of engine speed of 400 RPMs at different throttle positions have similar range of engine vibration. The preliminary conclusion was reached to state that different throttle positions did not affect the engine speed vibration.

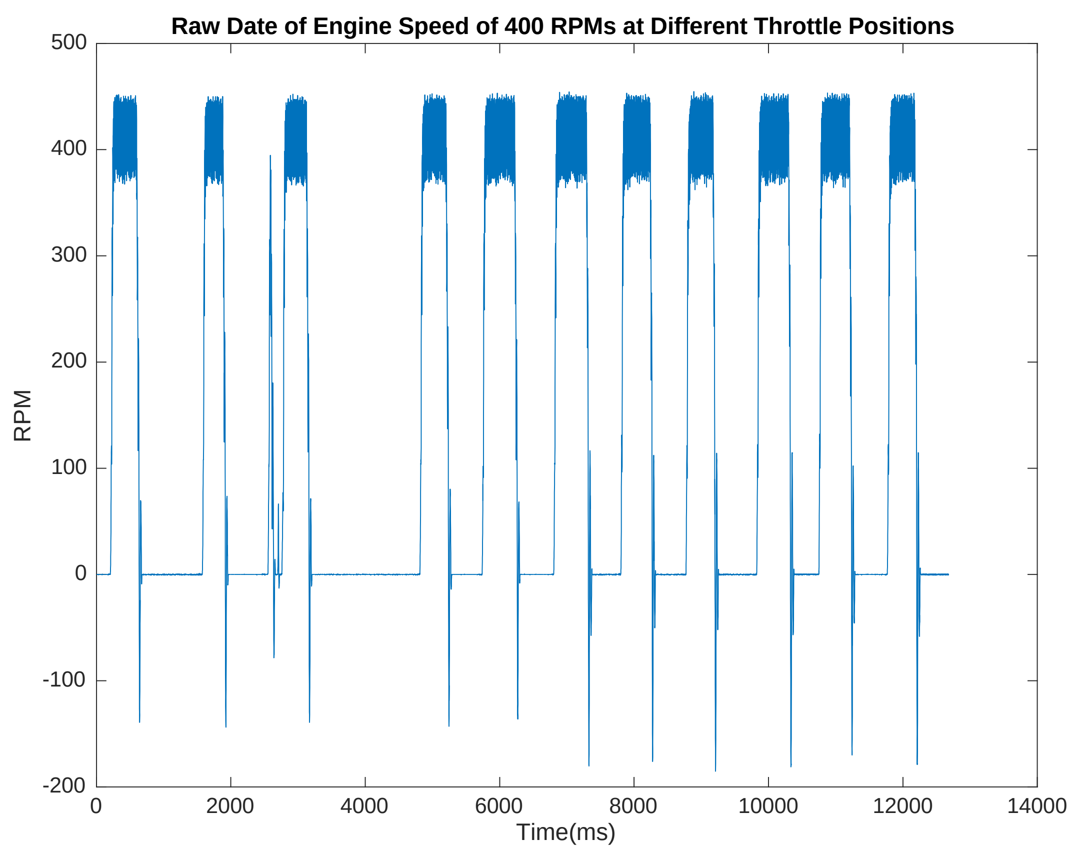

Figure 25 400 RPM Engine Speed at Different Throttle Positions

Further data analysis was conducted to verify the preliminary conclusion. In Figure 26, the average engine speed plot indicated that the lowest RPMs of the engine speed 400 RPMs occurred at 417.3 was only 1.7 RPMs less than the highest RPMs at 419. In other words, the highest engine speed occurred when throttle position was 90% opened while the lowest engine speed occurred when throttle position was 10% opened.

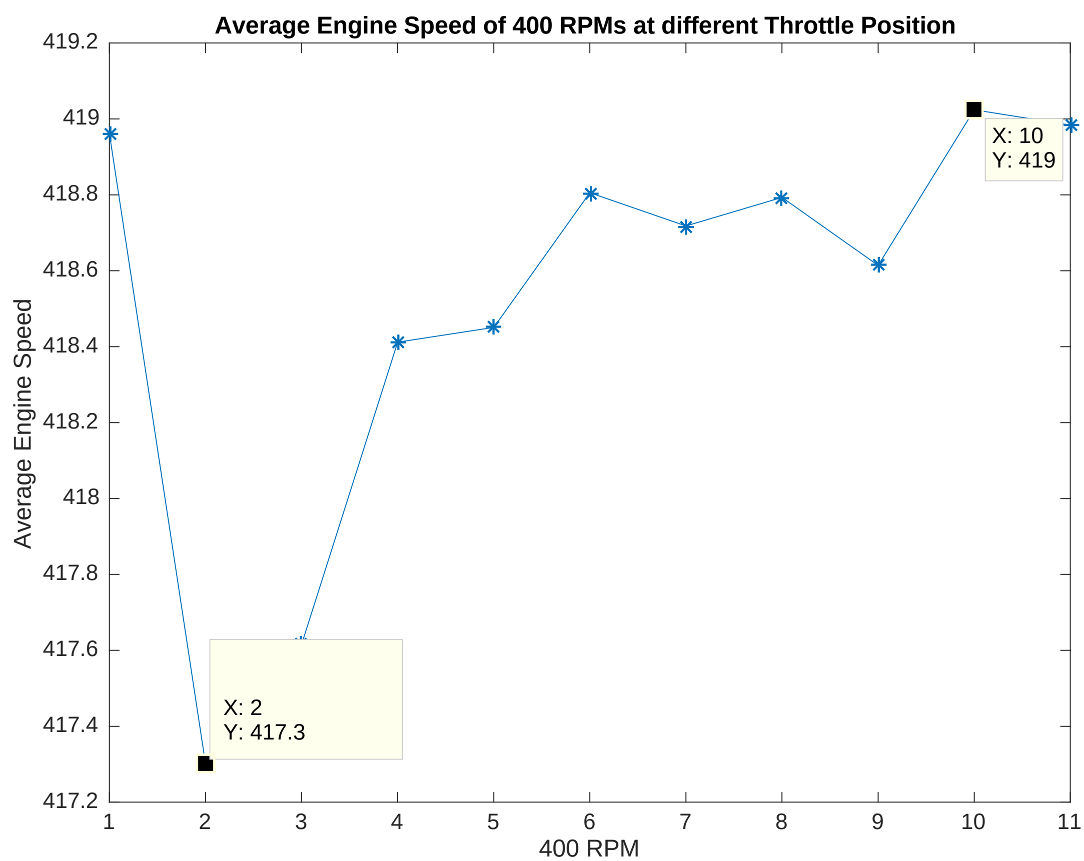

Figure 26 Average Engine Speed of 400 RPMs at Different Throttle Positions

In Figure 27, the standard deviation of the engine vibration at 400 RPMs at different throttle position indicated further that the throttle position would not affect the engine speed vibration. This testing was done at the 400 RPMs engine speed where the engine speed vibration was relatively large at this speed.

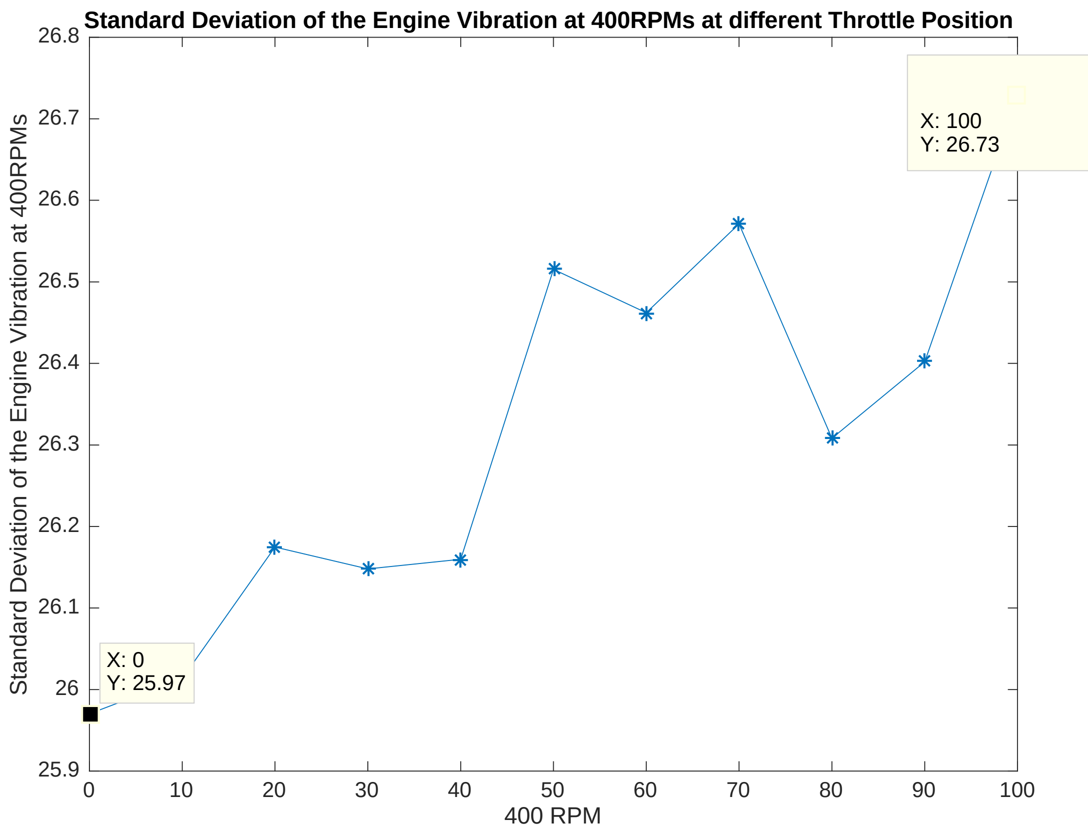

Figure 27 Standard Deviation of 400 RPM Engine Speed at Different Throttle Positions

Based on the engine speed testing at different throttle positions above, the team decided to set the throttle position to fully closed position when firing the engine.

To find out the engine firing RPMs for the control strategy, the engine firing RPM testing would be done with the emission data. The firing engine speeds were tested out from 800 RPMs with an increment of 100 RPMs to 1200 RPMs to see the variation of the emission data during the engine cold-start phase.

In Figure 28, the emissions data of NOx was collected at pre-CAT location from 800 RPMs to 1200 RPMs. The y axis indicated the peak value of NOx that the engine could produce at different engine firing RPMs. As it could be seen, the concentration of NOx would become smaller as the engine firing RPMs became higher. The emission of NOx was 704.6 ppm at the engine speed of 800 RPM. As the engine speed increased, the emission of NOx was 37.22 ppm at the engine speed od 1200 RPM.

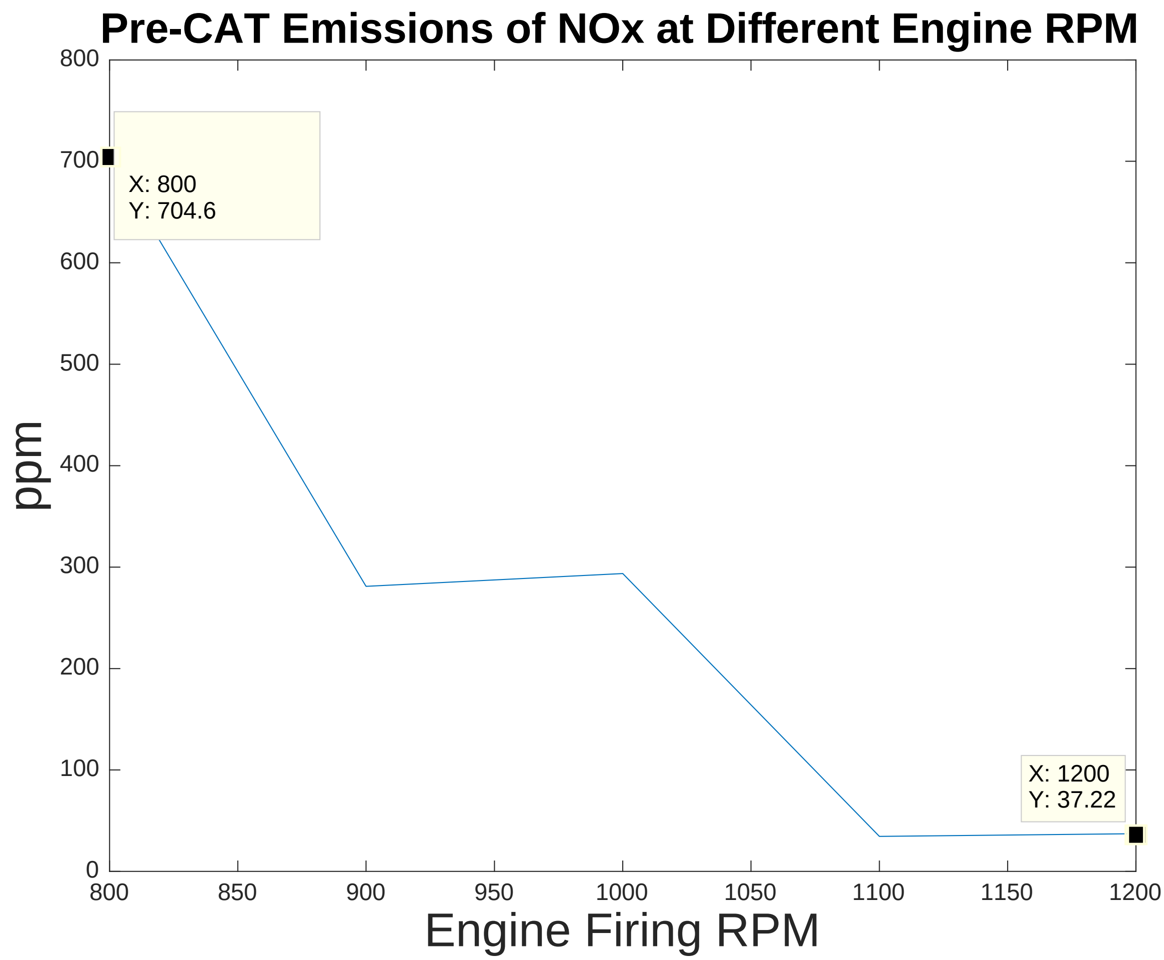

Figure 28 The Emission of NOx in the Pre-CAT Location at Different Engine Speeds

In Figure 29, the emissions data of CO was collected at pre-CAT location from 800 RPMs to 1200 RPMs. The y axis indicated the peak value of CO that the engine could produce at different engine firing RPMs. As it could be seen, the concentration of NOx would become larger as the engine firing RPMs became higher. The consistency of the testing results could be improved in the future to avoid the inconsistent change from 1100 RPMs to 1200 RPMs. At 800 RPM engine speed, the engine would produce 4.186 Vol% CO whereas 1200 RPM engine speed would produce 5.909Vol%.

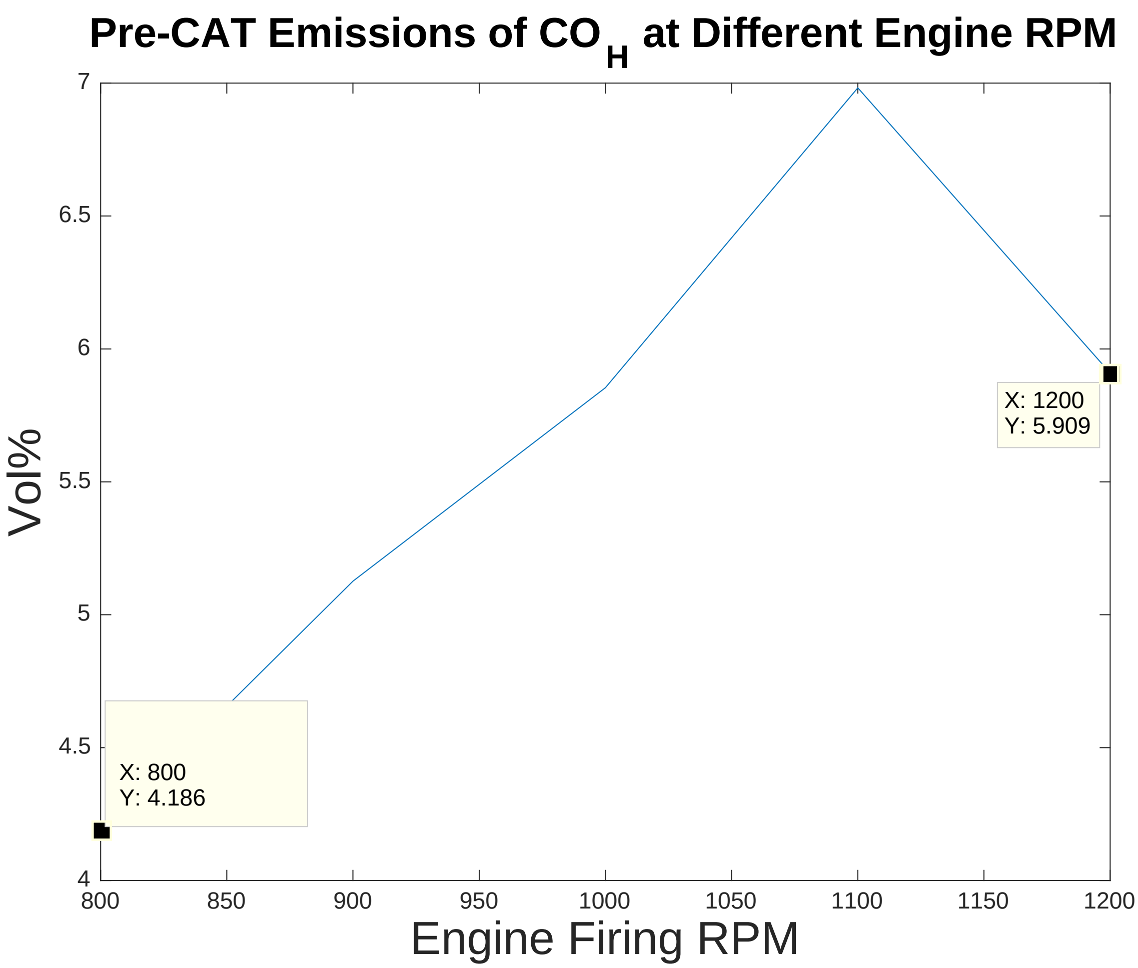

Figure 29 The Emission of CO in the Pre-CAT Location at Different Engine Speed

In Figure 30, the emissions data of THC was collected at pre-CAT location from 800 RPMs to 1200 RPMs. The y axis indicated the peak value of THC that the engine could produce at different engine firing RPMs. As it could be seen, the concentration of THC would become larger as the engine firing RPMs became higher. At 800 RPM engine speed, the engine would produce 1.02e+4 ppmC THC whereas 1200 RPM engine speed would produce 2.10e+4 ppmC THC.

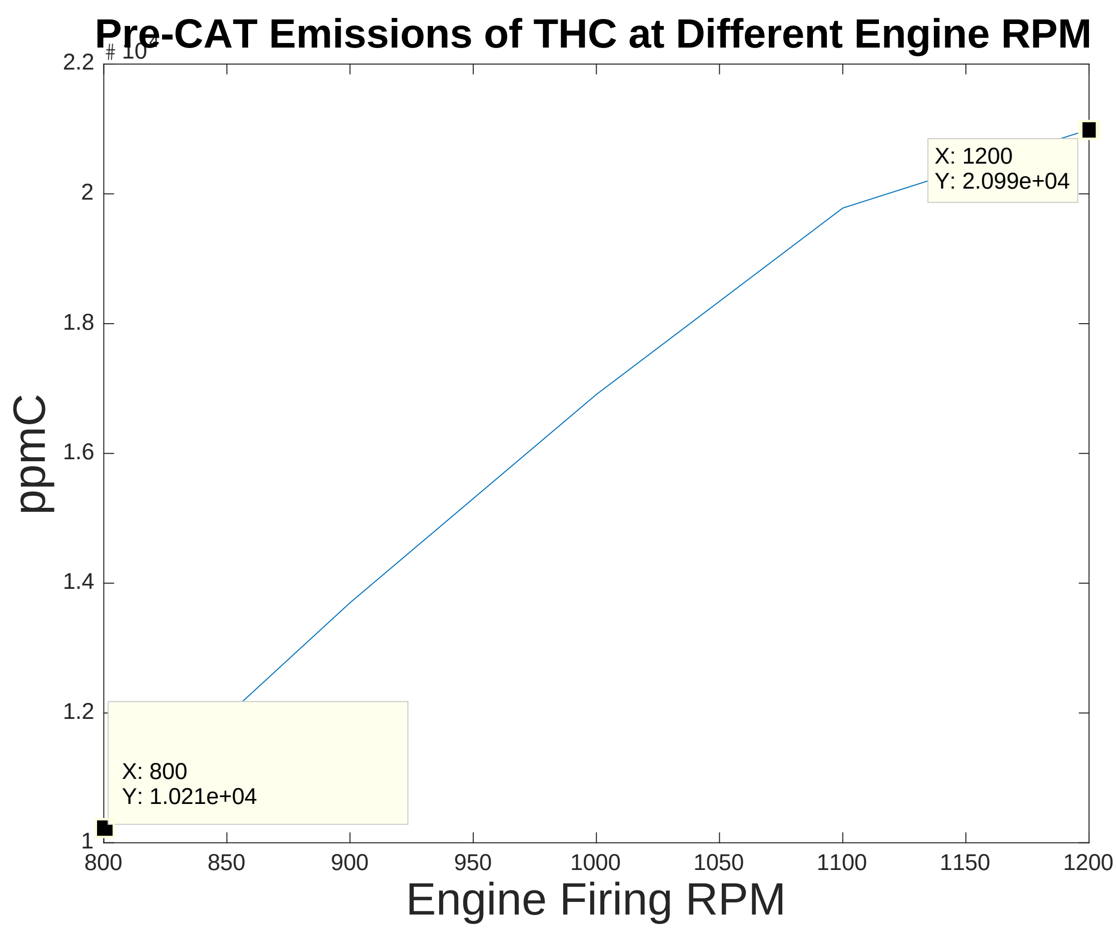

Figure 30 The Emission of THC in the Pre-CAT Location at Different Engine Speed

In the vehicle emissions, the relationship of THC and NOx were inversely formed. At lower RPM, it would cause more NOx but less THC. Consider the total amount of emissions it could reduce at lower RPM for THC and CO, it was more beneficial to fire the engine at lower engine speed. Based on the emissions testing results, it could reach a conclusion that 800 RPMs would be used in the control strategy to fire the engine since it could produce least amount of CO and THC after cold start although the amount of NOx would increase.

4 Validation

4.1 Control Strategy Development Validation

For this research, the validation testing was set up to test up two main focuses. First, the control strategy must be verified before implementing onto the EcoCAR vehicle. In the validation phase, the developed control strategy codes would be implemented in the Stateflow of the Matlab Simulink. This part of the engine start control strategy would take charge of the EHC heating phase. The dynamometer setting including EHC, power supply, solid-state relay and RTDs would also be installed on the vehicle. Eventually, this research needs to deliver the control criteria to develop a functional control strategy of EHC heating.

In Figure 31, there was a flow chart of the control strategy before implementing into the Stateflow which is part of Matlab Simulink.

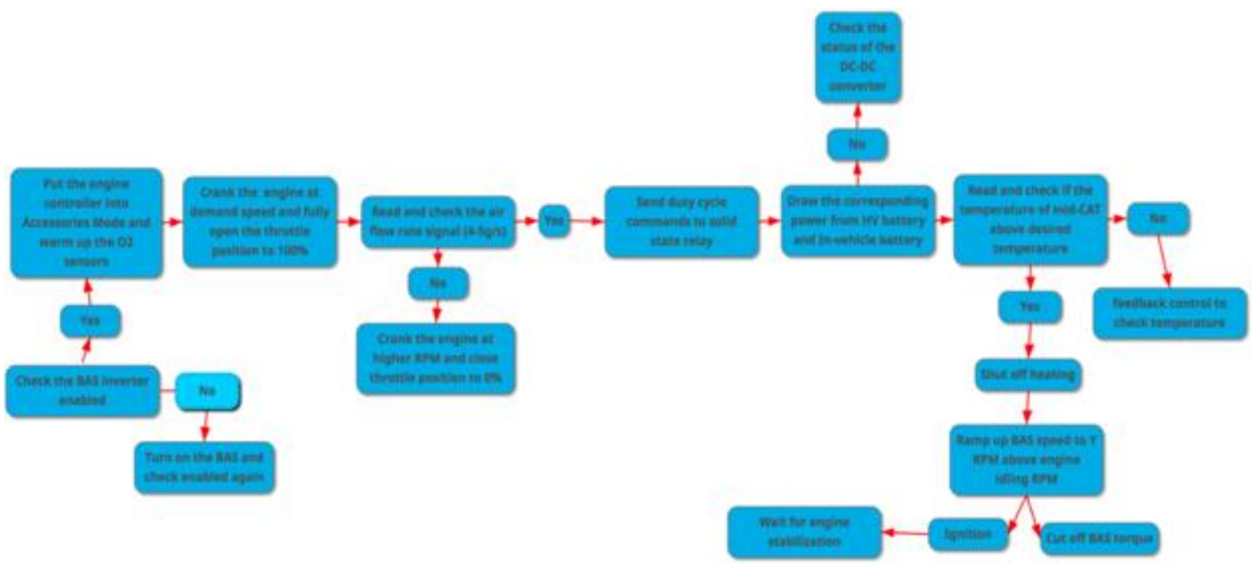

Figure 31 Flow Chart of EHC Pre-Heating Control Strategy

4.2 Emissions Reduction Validation

In this research, the main purpose was to reduce the primary emissions including NOx, THC and CO with the control strategy that could heat up the EHC with minimal power consumption in shortest time. To verify the effects of the EHC on emissions reduction, the emissions data testing would be conducted in two conditions. The first emission data testing would be conducted without the EHC heating. This first emissions data testing was to understand how many grams of three primary emissions data were produced before and after the EHC without the heating control strategy as a baseline emissions data. And the second emissions testing would be conducted with the EHC heating. This second emissions data testing was to understand how many grams of three primary emissions data were produced before and after the EHC with the heating control strategy.

Two emissions testing were conducted on the vehicle on the chassis dynamometer. The outlet of the exhaust tip was connected to the emissions analyzer. Both testing would be conducted with a completely engine cold-start. Based on the results of baseline emissions testing from the engine dynamometer, the EHC would take around 160 seconds to reach the steady state of emissions. The first baseline emissions testing would be conducted at least 3 minutes to understand the chemical characteristics of EHC on the vehicle. The second emissions testing would be conducted at least with a time length of allowing the emissions to reach the steady state. After completing the emission data testing, the conversion efficiencies would be calculated with the same equation.

5 Conclusion and Future Work

5.1 Conclusion

Throughout the research project, the control strategy for the EHC was successfully developed for the EcoCAR team. Some control criteria were determined based on the testing results from this research. First, the engine would be operated in electrical mode at 290 RPM with the fully opened throttle position to get an appropriate air flow rate. The engine speed at 510 RPM with the fully opened throttle position would be used as the backup plan to get the air mass flow rate if the air mass flow rate was not stable in other condition. The light-off temperature at $270\,°C$ would be used as the control criteria at the mid-CAT location for the EHC. With the consideration of emissions data, engine speed variation and throttle position, the engine was determined to fire at 800 RPM.

In addition to the determination of control criteria for the control strategy, there are some additional conclusions drawing from this research. First, both fully closed and opened could generate an increasing air mass flow rate as the engine speed increases. The emissions conversion efficiencies of NOx, THC and CO would not change greatly once the temperature of the EHC is above light-off temperature. As the BAS speed increase, the engine speed variation becomes less. The throttle position does not affect the engine speed variation. The last conclusion is that the engine produce less emissions at lower engine firing speed.

The unique power train of the PHEV allows the EHC to heat up in electrical mode before starting engine. With the control strategy of the EHC heating, the vehicle emissions were reduced greatly, especially for the THC and NOx. They were reduced as three times and ten times less as the previous emissions respectively. The emission of CO was also reduced as twice less as the previous emission. This EHC heating control strategy only takes about 36.7 W*h in 60 seconds to heat up the EHC.

5.2 Future Work

In the future, this research could be improved in two aspects. First, the control strategy for this research could be extended to use for the hot/warm engine restarts events. More thermal and chemical characteristics testing of EHC could be done after the engine stops operating from half hour to six hours. Additional work could also be done for the stop-start function on the vehicles. Besides, the thermal characteristics of the EHC in this research could be studied better if the 2D thermal model is created in the future work.

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